ERDC/CRREL TR-11-6

Cold Regions Research and Engineering Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

# Comparison of Hydraulic Conductivity Determinations in Co-located Conventional and Direct-Push Monitoring Wells

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March 2011

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# Comparison of Hydraulic Conductivity Determinations in Co-located Conventional and Direct-Push Monitoring Wells

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Final report



Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

**Abstract:** Determination of the hydraulic conductivity of a formation is needed for site assessment and remediation. This project examined whether direct-push (DP) monitoring wells can provide a measure of formation hydraulic conductivity similar to that provided by conventionally installed hollow-stem auger (HSA) wells using single-well test methods (i.e., slug tests). Four test sites with co-located DP and HSA wells were used. Soil types at the test sites were primarily fine- to medium-sized sands. DP-well installation methods included both hydraulically driven cone penetrometer (CPT) wells and hammered wells. The CPT wells typically relied on formation collapse around the well screen to form the filter pack. The remaining DP wells were constructed with pre-pack filters. The DP wells ranged in diameter from 1/2 in. to 2 in., and the lengths and depths of the screens were matched as closely as possible to those of the HSA wells. Whenever possible, pneumatic slug tests were performed. Where the wells were screened across the water table, however, a packer was used in conjunction with the pneumatic test in the larger wells and a mandrel test method was used in the smaller wells.

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# Preface

The U.S. Army Corps of Engineers Long-term Monitoring Program at the Engineer Research and Development Center (ERDC) provided the funding for this project. We wish to thank our project monitors Tony Bednar (ERDC Environmental Laboratory [EL]) and Denise MacMillan (formerly with ERDC-EL) for their support of this work. We are also grateful to the Environmental Security Technology Certification Program for previously funding the installation of the co-located conventional and direct-push monitoring wells (for a previous demonstration) that we used in this study.

We thank Thomas Best, the point of contact (POC) at Hanscom Air Force Base (AFB), and Joe McLernan, the POC for Tyndall AFB, for their help at each of the sites. Special thanks go to Tim McHale, the POC for Dover AFB, who was instrumental in our successful field work at Tyndall and Dover AFBs. We also thank Tom Christy and others at Geoprobe Systems for their support and patience while this study was being conducted and Dr. Jim Butler, Kansas Geological Survey, for his advice and comments during this project and over the years. Special thanks go to our reviewers, Jeffrey Farrar with the Bureau of Reclamation (Denver, CO) and Brian Striggow with Region 4, U.S. Environmental Protection Agency, for their useful comments and suggestions.

The work was performed under the general supervision of the Geochemical Sciences Branch (RR-N) of the Research and Engineering Division (RR), Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Dr. Terrence M. Sobecki was Chief, RR-N; Dr. Justin Berman was Chief, RR; and Kevin Knuuti was Technical Director for Earth Sciences and Engineering. The Deputy Director of CRREL was Dr. Lance Hansen and the Director was Dr. Robert E. Davis.

CRREL is an element of ERDC. The Commander and Executive Director of ERDC was COL Kevin J. Wilson, and the Director of ERDC was Dr. Jeffery P. Holland.

# Unit Conversion Factors

| Multiply | By | To Obtain |
|---|---|---|
| feet | 0.3048 | meters |
| inches | 0.0254 | meters |
| miles (U.S. statute) | 1,609.347 | meters |
| pounds (force) per square inch | 6.894757 | kilopascals |

# Acronyms

| | |
|---|---|
| A/D | analog to digital |
| AFB | Air Force Base |
| ANOVA | Analysis of Variance |
| ASTM | American Society for Testing and Materials |
| bgs | below ground surface |
| CPT | cone penetrometer |
| $C_D$ | dampening coefficient |
| CRREL | Cold Regions Research and Engineering Laboratory |
| DoD | Department of Defense |
| DP | direct-push |
| EPA | U.S. Environmental Protection Agency |
| ERDC | U.S. Army Engineer Research and Development Center |
| HSA | hollow-stem auger |
| ID | inside diameter |
| ITRC | Interstate Technology and Regulatory Council |
| ln | natural log |
| msl | mean sea level |
| PVC | polyvinyl chloride |
| RSD | Relative Standard Deviation |
| UST | underground storage tank |

# 1 Introduction

## Background

Groundwater monitoring wells are used in site assessment, remediation, and long-term monitoring. The installation of monitoring wells with direct-push (DP) methods has grown significantly in the past decade as DP technology has matured. When monitoring wells are installed in unconsolidated formations, DP methods provide time and cost savings and minimize the production of hazardous wastes when compared with traditional rotary drilling. Several recent studies (McCall et al. 1997; Kram et al. 2000; BP Corp. and the UST Programs for EPA Regions 4 and 5, 2002; Kram et al. 2003; Major et al. 2009) have shown that DP wells can provide representative water quality samples for environmental purposes when installed correctly (i.e., using American Society for Testing and Materials (ASTM) practices such as D6724 and D6725 [ASTM 2004b, 2004c]). However, relatively little data has been available on whether DP wells can be used to provide representative measurements of formation hydraulic conductivity by single-well test methods (i.e., slug tests). The hydraulic conductivity of a formation is an important component of site assessment and remediation. It is needed to model analyte transport, to develop an effective remediation strategy, and to perform risk assessment. Therefore, it would be advantageous if DP wells could be used to measure this important parameter.

Slug tests are the most widely used method for field determination of hydraulic conductivity at contaminated sites (Butler 1997; Henebry and Robbins 2000; Bartlett et al. 2004). For a traditional slug test, the static water level in a well is either raised by pouring water into the well (i.e., a slug-in. test) or lowered by removing water from the well (i.e., a slug-out test). The water level recovery curve data and the formation and well geometry parameters are then used in an analytical model to determine the hydraulic conductivity of the formation (Butler 1997; Hvorslev 1951; Bower and Rice 1976; ASTM 2008 [i.e., D4044]).

The aquifer-well system responds to an instantaneous change in head (i.e., slug test) in two primary ways. The most common response observed is the log response, which is sometimes referred to as over damped behavior

(Figure 1). For this type of well response, when water level recovery data are plotted on a semi-log graph, with time on the logarithmic y-axis and head on the (linear) x-axis, a straight line is obtained. Straight-line models of these responses along with well geometry data are then used to calculate the formation hydraulic conductivity. Two widely accepted methods have been developed for modeling this type of aquifer response. The Hvorslev (1951) model is generally used to model the data in confined aquifers. The Bouwer and Rice (1976) model was developed to model over-damped responses in unconfined aquifers.

The other primary response, yet less commonly observed, is the under-damped response (Figure 2). This aquifer-well system behavior is similar to when a spring is pulled and released and oscillates back and forth until it returns to its static state. These under-damped or oscillatory responses are modeled in a similar fashion to under-damped spring behavior using a dampening coefficient ($C_D$) and time modulation (t*d/t*) to match field response data to model curves (Butler et al. 2003; Butler 1997).

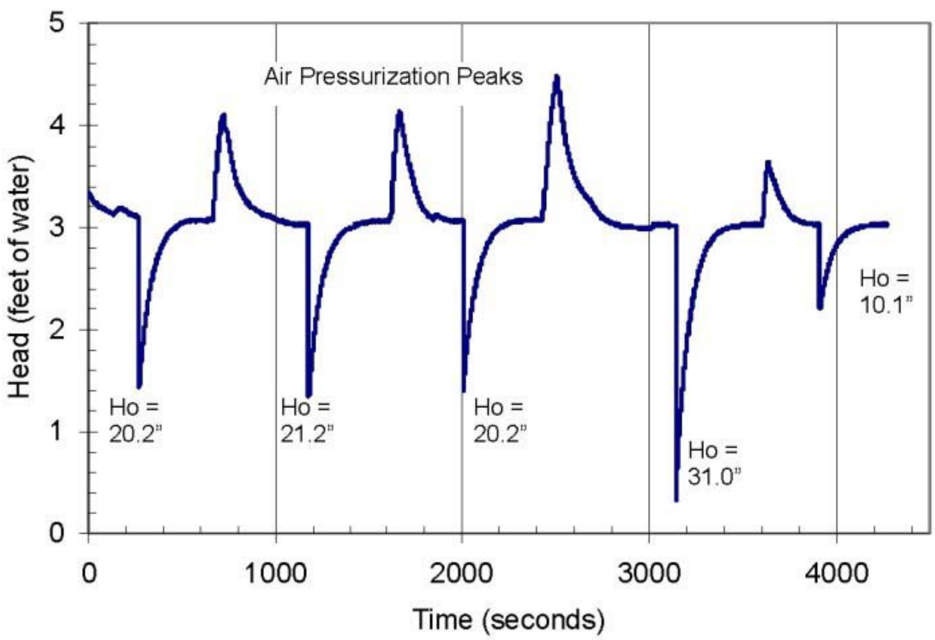



**Figure 1. Over-damped slug-test responses.** These slug-test responses were conducted in a 4-in. diameter HSA well (MW 09 at CRREL). The five rising-head slug tests display typical over-damped behavior. The initial head (Ho) values were recorded from the pressure gauge on the pneumatic head and indicate the number of inches the water level was lowered in the well to induce the slug test.

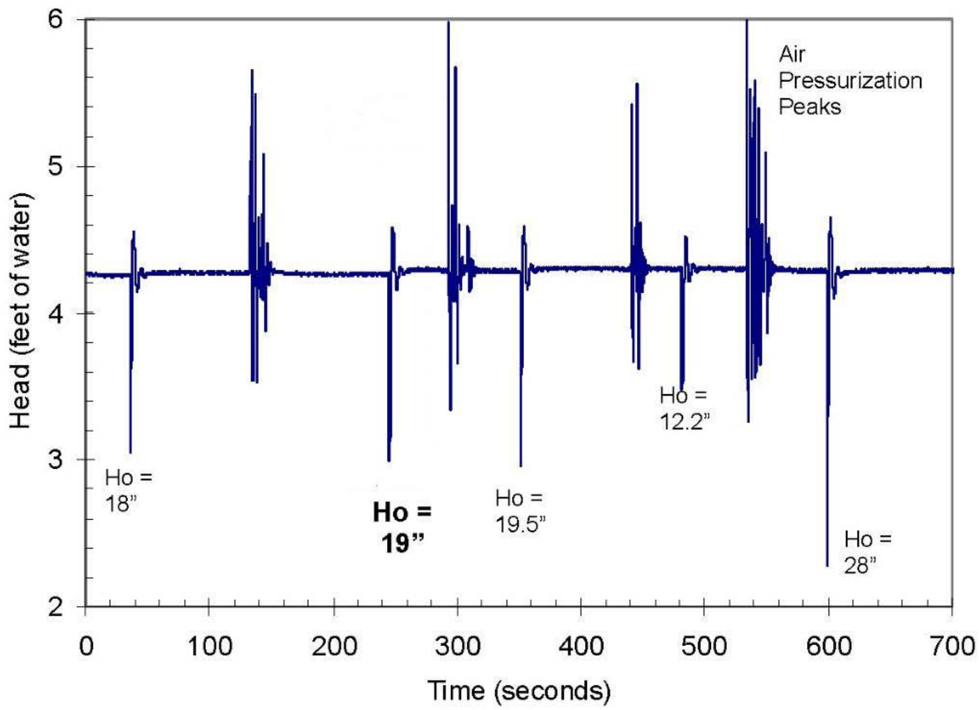



**Figure 2. Under-damped slug-test responses.** A series of five pneumatic slug tests performed on a ½-in. DP well (MW 02 at Tyndall AFB).

Previously, conventional slug tests were limited to formations that had relatively lower conductivities (i.e., less than $10^{-4}$ cm/s). With the development of pneumatic methods (Prosser 1981; Leap 1984; Orient et al. 1987; McLane et al. 1990), slug tests could be performed in formations that had higher conductivities, and models that dealt with oscillatory responses (common to high permeability formations) were developed (i.e., Van der Kamp 1976; Kipp 1985; Springer and Gelhar 1991; Butler 1997; McElwee and Zenner 1993; Butler and Garnett 2000).

Among the factors that affect slug-test results are the well design geometry (e.g., casing inside diameter [ID], intake radius, intake length, and radius of influence [when applicable]), and the drilling method and its associated formation disturbance. DP wells are installed either by static pushing using a hydraulic ram mounted on a vehicle such as a cone penetrometer (CPT) truck or by hammering drive points and rods into the ground using a percussion hammer rig (e.g., made by Geoprobe, Salina, KS) mounted on a truck or tracked vehicle. This action can cause compaction and lower hydraulic conductivities in the formation immediately adjacent to the well.

DP wells can be installed using either an exposed-screen technique or a protected-screen technique. With the first technique, the riser and screen

are either pushed directly, or the riser and screen are mounted on the outside of the drive rod. Because the well screen is exposed during installation, it is especially important that these wells be properly developed upon completion. For the protected-screen installation, the riser and screen can be installed by lowering the casing and screen into the drive rod or outer casing once the target depth is obtained. Wells that are installed using the protected-screen method are consistent with conventional monitoring well construction techniques such as ASTM Method D5092-04e1 or U.S. Environmental Protection Agency (USEPA 1991) in that an annular seal and filter pack can be incorporated into the well design (ITRC 2006).

To install a filter pack, the sand can be tremmied (poured) into the hole around the well screen, or it can be installed as a single unit pre-pack well screen (often referred to as pre-pack wells). Some DP wells have no added filter pack material and are often referred to as drive points. For these wells, the formation needs to collapse around the casing and screen to form a “natural” filter pack; these wells will be referred to frequently as no-pack wells in this report. Currently, there are ASTM methods for installation of DP wells (i.e., ASTM D6724-04 and D6725-04), and the Interstate Technology and Regulatory Council (ITRC) Sampling, Characterization, and Monitoring (SCM) team has published a guidance document on the use of DP wells for long-term monitoring (ITRC 2006). The USEPA has also published a guidance document on the use of direct push methods for groundwater sampling and monitoring (USEPA 2005).

In contrast, hollow-stem auger (HSA) wells are installed in fairly large-diameter holes that were drilled using auger flights. The action of the drill bit and flights can cause the soil adjacent to the hole to loosen, resulting in increased hydraulic conductivity in the soil directly adjacent to the hole, or loosened fines can close the formation near the hole, which decreases hydraulic conductivity.

For any monitoring well, proper well development is important to ensure that there is a good hydraulic connection between the well and the surrounding formation. Well development removes any artifacts that were created during well installation, such as disturbed fines near the borehole and silts and clays that may have been smeared along the walls of the borehole, and can impact the hydraulic connection between the well and the formation (ITRC 2006).

Given that the differences in installation and construction of conventional and DP wells could affect determination of the hydraulic conductivity (K) for a formation, two questions arise. Can DP wells be used to determine a K value for a formation? If K values for DP wells differ from those determined from a conventional well, does one of the well types provide a more accurate assessment of the hydraulic conductivity of the formation?

As part of a study that compared analyte concentrations from co-located conventionally installed HSA and DP wells at Port Hueneme, CA (Kram et al. 2003; Major et al. 2009), Bartlett et al. (2004) conducted a study that compared the K values derived from the same co-located conventional HSA and DP wells. The wells used in the Bartlett study consisted of four well clusters; although most of the tests were conducted in clusters B1 and B2. Each well cluster was screened over a different depth interval (Figure 3). Each well cluster contained five types of wells: (1) a 2-in. diameter conventionally installed HSA well, (2) a 2-in. diameter ASTM-designed pre-pack DP well, (3) a 3/4-in. diameter ASTM-designed pre-pack DP well, (4) a 3/4-in. diameter conventionally designed pre-pack DP well, and (5) a 3/4-in. no-pack DP well. For each of the clusters, the screen depth and length of the DP wells was matched as closely as possible to that of the

| Cluster | Screen Length | Screen Interval |
|---|---|---|
| B1 | 2 ft. | 10 to 12 ft. |
| B2 | 5 ft. | 7 to 12 ft. |
| B3 | 2 ft. | 16 to 18 ft. |
| B4 | 5 ft | 12.5 to 17.5 ft. |

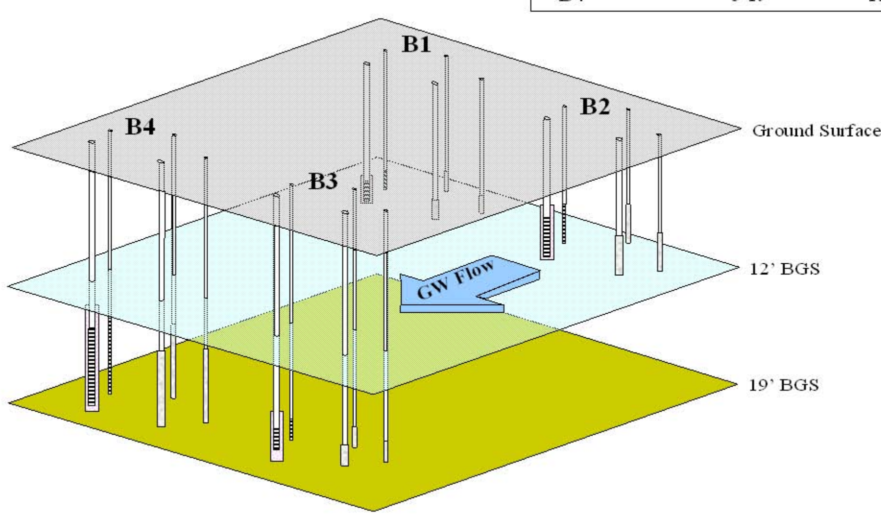



Figure 3. Three dimensional view of the monitoring wells in test cell B (Kram et al. 2001). Arrow shows direction of groundwater flow.

conventional well in that cluster. The wells were screened between 7 to 17.5 ft below ground surface (bgs) in fluvial-deltaic sediments consisting of medium- to coarse-grained sand and gravel. During these tests, the screens were fully submerged.

Bartlett et al. (2004) concluded that short-duration pneumatic slug tests were a viable approach for determining the hydraulic conductivity values in a highly permeable formation (with a mean K value of $2 \times 10^{-2}$ cm/sec). They found no significant difference between the pneumatic slug tests and steady-state pumping tests of the aquifer. They also found that the K values in DP wells were independent of pre-pack design, well radius, induced head, and test method (assuming the same screened interval). Analysis of Variance (ANOVA) tests revealed that the pre-pack wells had no statistically significant differences, and the no-pack DP wells and the drilled wells had no significant differences between them. However, there was a significant difference between the drilled wells and the pre-pack wells. Bartlett et al. (2004) noted that the variance associated with the hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average K values from wells of the same type. They concluded that the differences in the K values observed among the wells were largely due to formation spatial heterogeneity rather than differences in well construction and installation or in test method.

## Objectives

The purpose of this project was to determine if co-located DP and HSA installed monitoring wells provide a similar measure of formation hydraulic conductivity when screened over the same interval. Furthermore, the project examined the precision of the slug tests in the DP and conventional wells.

## Approach

Single-well test methods (i.e., slug tests) were used to determine the K values in DP and conventionally installed HSA wells. Four Department of Defense (DoD) test sites with co-located DP and conventional HSA monitoring wells were used. The screen length and depth of the DP wells at these sites were matched to that of the conventional wells. DP well types included hydraulically-driven Cone Penetrometer (CPT) wells that rely on the collapse of the formation to form the filter pack, and percussion-driven wells with pre-pack screens.

# 2 Materials and Methods

## Sites and wells selected for study

A limited number of facilities around the country have co-located DP and HSA-installed monitoring wells. A previous study funded by the DoD Environmental Security Technology Certification Program (ESTCP) compared both organic and inorganic analyte concentrations from co-located DP and conventional wells at five DoD tests sites (Kram et al. 2003; Major et al. 2009). These sites included Tyndall Air Force Base (AFB) (FL), Hanscom AFB (MA), Dover AFB (DE), U.S. Army Engineer Research and Development Center's (ERDC's) Cold Regions Research and Engineering Laboratory (CRREL) (NH), and Port Hueneme (CA). As mentioned previously, Bartlett et al. (2004) compared the K values determined from conventional and HSA wells with four types of DP wells at the Port Hueneme site.

The remaining four test sites were selected for this study: Tyndall, Dover, and Hanscom AFBs and CRREL. Table 1 summarizes information about the wells for each of these test sites. Appendix A maps show well pair or well cluster locations for each of the test sites. Available information on geology and hydrogeology for each facility is provided in Appendix B. Many of the conventionally designed wells used for this study were several years old. Older wells are potentially subject to aging problems such as "silting-in." and biofouling. Replicate tests in most of these (conventional) wells provided repeatable results indicating that these aging problems were not a significant factor in well performance.

## Test plan

Slug tests were conducted in co-located conventional HSA wells and various types of DP wells at the four test sites. Whenever feasible, the field team performed three replicate slug tests with the same initial head displacement. For the wells that had long recovery times (exceeding 20 minutes per test), three replicate tests were not always performed. The replicate tests allowed the field team to determine if the wells were adequately developed and provided a measure of the precision of these tests.

Table 1. Selected facilities and wells.

| Facility Name | Facility Location | Geologic Setting | # Co-located wells | Types of DP Wells | Types of Drilled Wells | Range of Depths (approx.) |
|---|---|---|---|---|---|---|
| Hanscom AFB | Hanscom, MA | Glaciolacustrine | 20 | 2-in. no-pack | 2-in. HSA | 8 to 21 ft |
| Tyndall AFB | Tyndall, FL | Marine Depositional | 36 | 0.5-in. prepack<br>1-in. prepack<br>1.5-in. no-pack | 2-in. HSA | 12 to 37ft |
| Dover AFB | Dover, DE | Marine Depositional | 18 | 2-in. no-pack<br>0.75-in. no-pack | 2-in. HSA | 20 to 31 ft |
| CRREL | Hanover, NH | Glaciofluvial & Glaciolacustrine | 9 | 0.5-in. prepack<br>0.75-in. prepack | 4-in. HSA | 115 to 140 ft |

Typically, the field team performed five rising-head and five falling-head tests on the wells. Most often three tests were performed with the initial head value ($H_o$) equal to ~20 in. of water displacement. This was followed by one test with $H_o$ ~10-in. and one test with $H_o$ ~30 in. of water displacement. Replicate tests with different initial head values were performed at most wells when time and conditions permitted.

The K values determined from these tests were used to determine if there were statistically significant differences between the K values of the various well types, test types (i.e., rising-head tests vs. falling-head tests), and locations.

## Field methods

The following sections review the field methods used in this study including the slug test equipment, slug test methods, well redevelopment, and the methods used to model the slug test responses.

### Slug-test equipment and methods

Slug tests of the DP and conventional wells were conducted using either pneumatic or mechanical methods. The pneumatic method is often preferred because it can provide high quality data with less noise than what can normally be achieved using mechanical slug-testing methods. This method is especially useful when oscillatory (or under-damped) responses are obtained during the slug tests. However, when wells are screened across the water table, pneumatic methods cannot be used to induce a change in head because air will be lost to the formation through the well screen. Under these situations, two different methods were used. For wells

with nominal ID of 1.5–2 in., a small inflatable packer with a small-diameter riser was used to conduct pneumatic testing (when aquifer and field conditions suggested this was the optimal method). For smaller diameter wells (i.e., 1-in. ID or less) that were screened across the water table, pneumatic slug-test methods were not possible. Under these conditions, a mandrel with an integral transducer was used to induce rising and falling-head slug tests by mechanical methods.

*Pneumatic slug-test system*

When appropriate, pneumatic slug tests were performed according to procedures described in ASTM Standard Practice D7242-06, the Pneumatic Slug Test System Standard Operating Procedure (Geoprobe 2002), and Butler (1997). A simple pneumatic slug-test system was used to perform these slug tests (Figure 4). The $H_o$ for each slug test was monitored by the

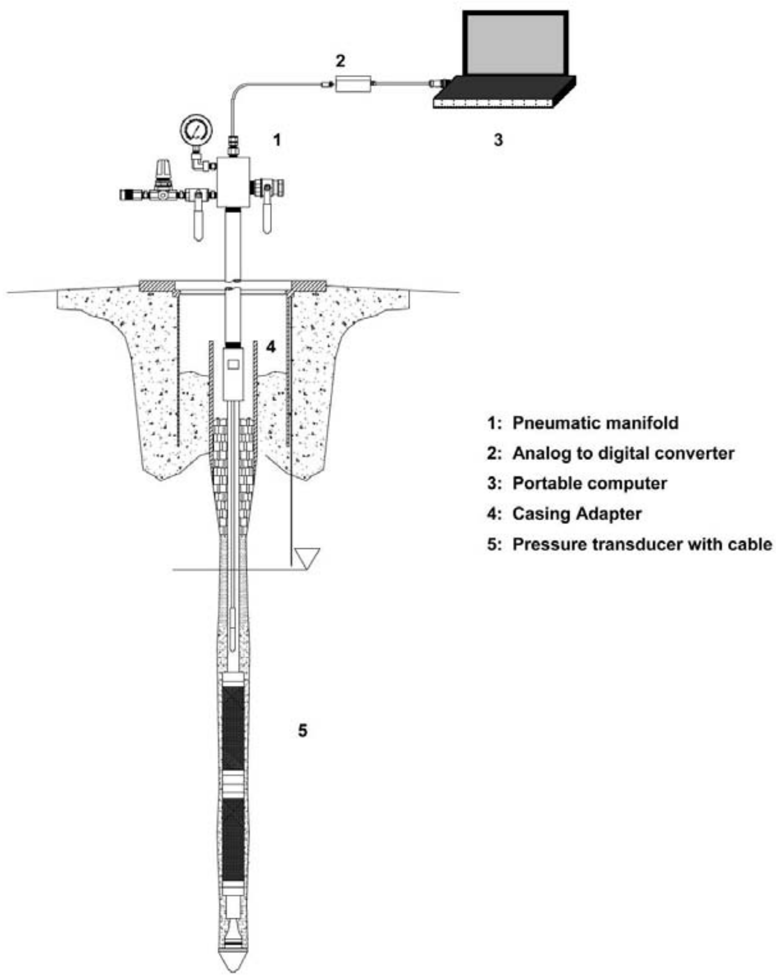



Figure 4. Diagram of a pneumatic slug-test system and its major components.

pressure gauge on the pneumatic head, which is graduated in inches of water. Thus the initial head is reported in inches of water lowered for a rising head test, or inches of water raised for a falling-head test. The water level changes induced by the slug test were measured with a 10-psi pressure transducer installed below the water level. An analog-to-digital (A/D) converter was used to convert the signal to a digital format transferred from the transducer to a notebook computer. The A/D system permits acquisition of transducer signals at 1, 2, and 10 Hz for optimal monitoring of the aquifer response to the slug test. Data were viewed onscreen as the tests were conducted and then saved to a file for later review and analysis.

*Small pneumatic packer system*

Most of the wells used in this project were screened across the water table, so a pneumatic method could not be used directly. For wells with nominal ID of 1.5–2 in., a small inflatable packer with a nominal 1/2-in. riser was used to seal off the screened interval across the static water level. Then pneumatic tests were performed through the riser of the packer system as shown in Figure 5. The pneumatic head, transducer, and data acquisition system (discussed previously) were used with the inflatable packer.

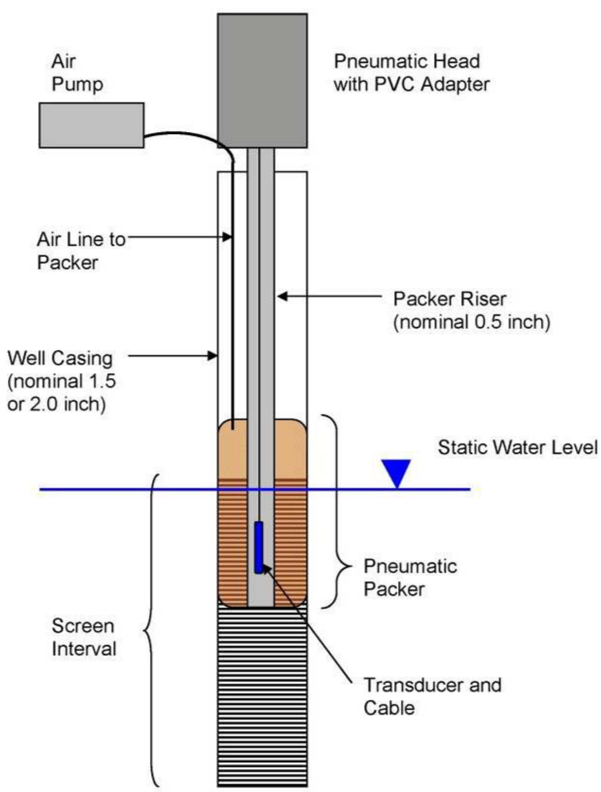



Figure 5. Diagram of the inflatable packer installation.

However, many of the tests performed with the packer system displayed reduced pressure changes ($H_o$) at the transducer as compared to observed pressure changes ($H_o$) at the pressure gauge on the pneumatic head. The observed pressure reduction was as much as 60–80% less at the transducer than at the pressure gauge. Review of appropriate literature (Zurbuchen et al. 2002; Butler et al. 2003) suggested this reduction in pressure may be the result of acceleration of the water column. Acceleration of the water column against gravity during rising-head tests will cause the pressure transducer to experience reduced pressure because the downward (gravitational) force exerted by the water column is reduced due to the acceleration of the water column in the opposite direction at a significant proportion of the gravitational acceleration rate.

To evaluate the possible influence of water column acceleration on the transducer response observed during the packer tests, an existing spread sheet was modified to model for this effect. Multiple attempts to obtain acceleration model fits for several data sets were only marginally successful. The acceleration model could not produce model curves that fit the field data from the transducer; an example is shown in Figure 6a for a well at Dover AFB. The field data exhibited much greater reduction in $H_o$ at the pressure transducer than the acceleration model produced for the well construction and slug-test geometry of actual field set up. Also, the phase shift of the acceleration model did not fit the wave-form of the actual field data. However, it was found that standard normalization procedures for these tests provided good fit to the standard model curves. In addition, non-normalized and normalized plots of the $H_o$ with time clearly indicated these tests conformed to conventional slug-test theory and were acceptable to model in that fashion (Figures 6b and 6c).

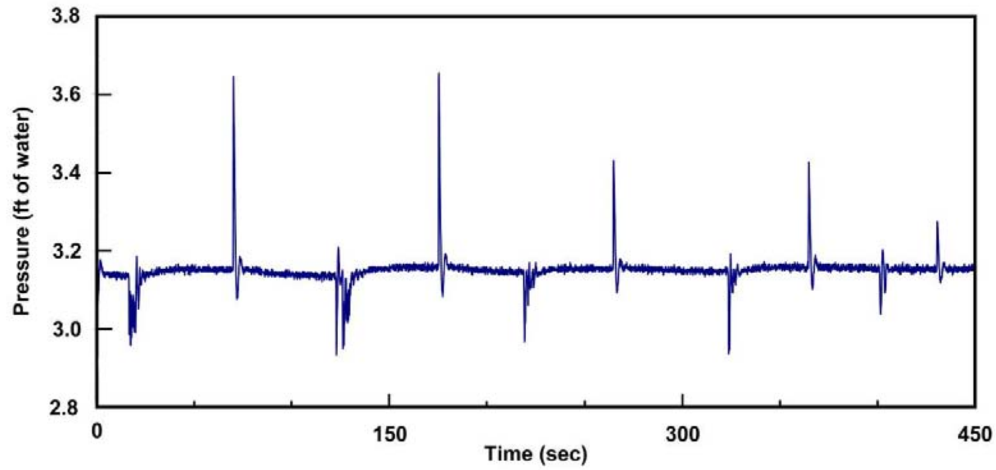



**Figure 6a. Plot of falling-head tests conducted in this well.** Pneumatic slug tests were performed using an inflatable packer system with schedule 80 nominal ½-in. polyvinyl chloride (PVC) riser. The first two tests had $H_o$ of approximately 20 in. of water displacement. The third and fourth tests had $H_o$ of approximately 10 in., and the fifth test had $H_o$ of approximately 5.0 in. of water displacement. Note that the transducer-observed pressure on the first two tests is only about 0.6 ft. This is about 30% of the 20 in. of water pressure observed on the pressure gauge of the pneumatic head. The other slug tests show a similar reduction of transducer pressure as compared to the gauge pressure for this series of tests. In general, the transducer-observed pressure is always somewhat less than the ideal $H_o$ pressure applied for slug tests. This phenomenon is due to several factors and is the topic of current and ongoing research. The tests shown here are extreme examples of this behavior.

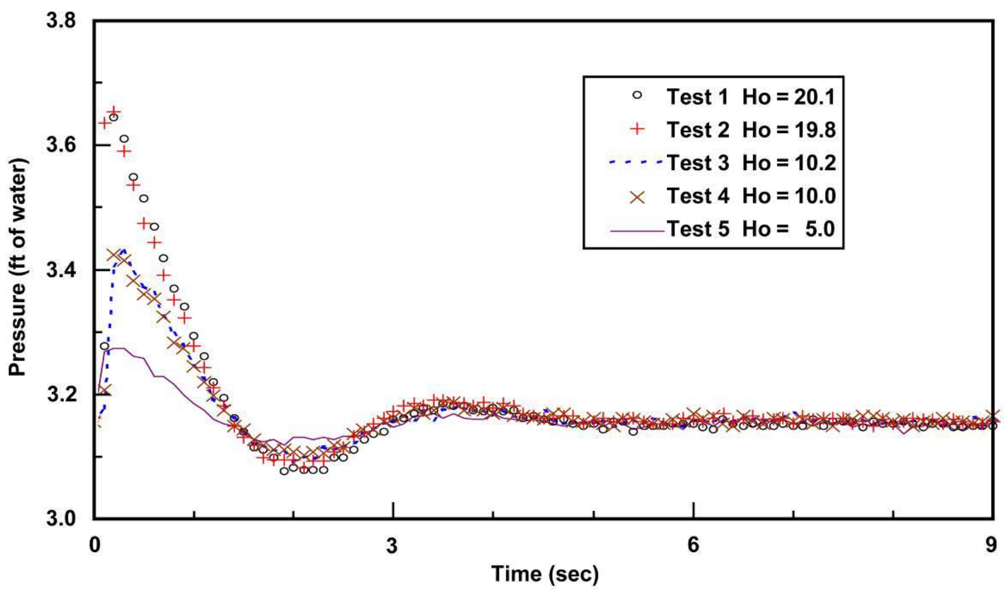



**Figure 6b. Plots of the five falling-head tests performed at this well.** This non-normalized plot demonstrates the well/aquifer system responded to the different $H_o$ values appropriately, with proportionally increasing displacement and symmetrical recovery curves. This indicates good test quality.

**Figure 6. Slug-test responses in a 2-in. CPT well (NTS235D Duplicate) at Dover AFB.**

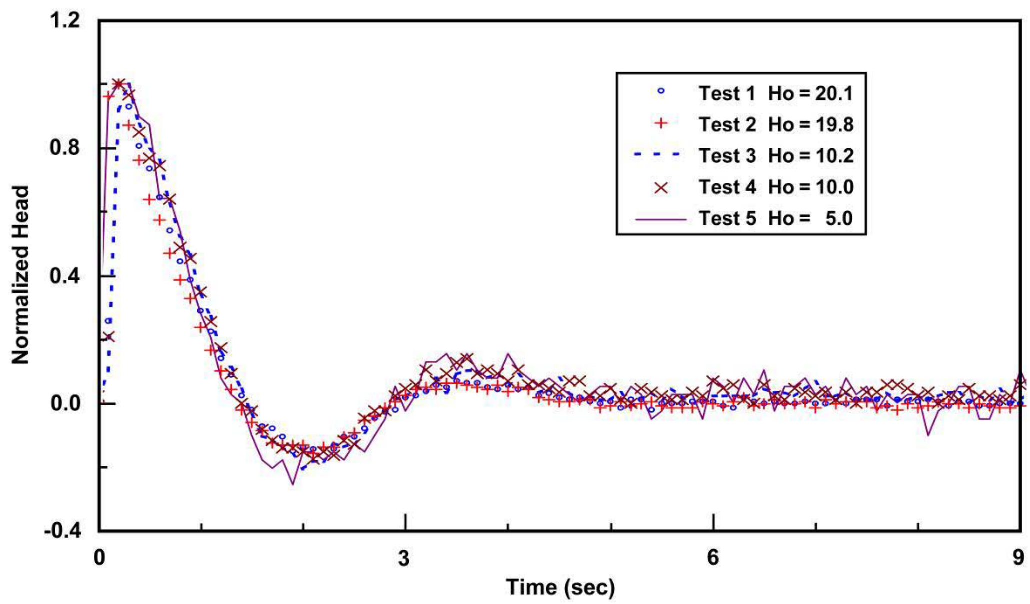



**Figure 6c. Normalized plots of the previous five slug tests.** The close correlation of the normalized plots with differing $H_o$ values demonstrates that the well/aquifer system responds linearly over the range of head values used to initiate the tests and, as such, conventional modeling theory is applicable. This is especially interesting here due to the reduced transducer readout as compared to the pressure gauge reading observed on the pneumatic head. Also, notice that the noise is slightly greater due to the small signal relative to baseline; this is especially true for the 5-in. $H_o$ test.

Figure 6 (Cont'd). Slug-test responses in a 2-in. CPT well (NTS235D Duplicate) at Dover AFB.

*Mandrel with integral transducer*

For the smaller diameter wells (i.e., 1-in. ID or less) that were screened across the water table, pneumatic slug-test methods were not possible. Under these conditions, a mandrel with an integral transducer was used to induce rising and falling-head slug tests by mechanical methods (Figure 7).

This method was effective in lower K formations and even in moderate K formations when the screen length was not too long (10 ft or less). However, when the well screens were relatively long (10 ft or greater) and were in formations with a moderate K, it was difficult to obtain representative slug tests with the mandrel method. This difficulty was either due to the noise created by the quick movement of the mandrel at the start of a slug test or to the mandrel interfering with the movement of water in the small-diameter wells. Conversely, the mandrel with integral transducer proved to be effective in some of the 1.5- and 2-in. wells with slower recovery rates. In all cases, the $H_o$ values given in the tables are for the distance the mandrel was moved vertically rather than the actual change in water level.

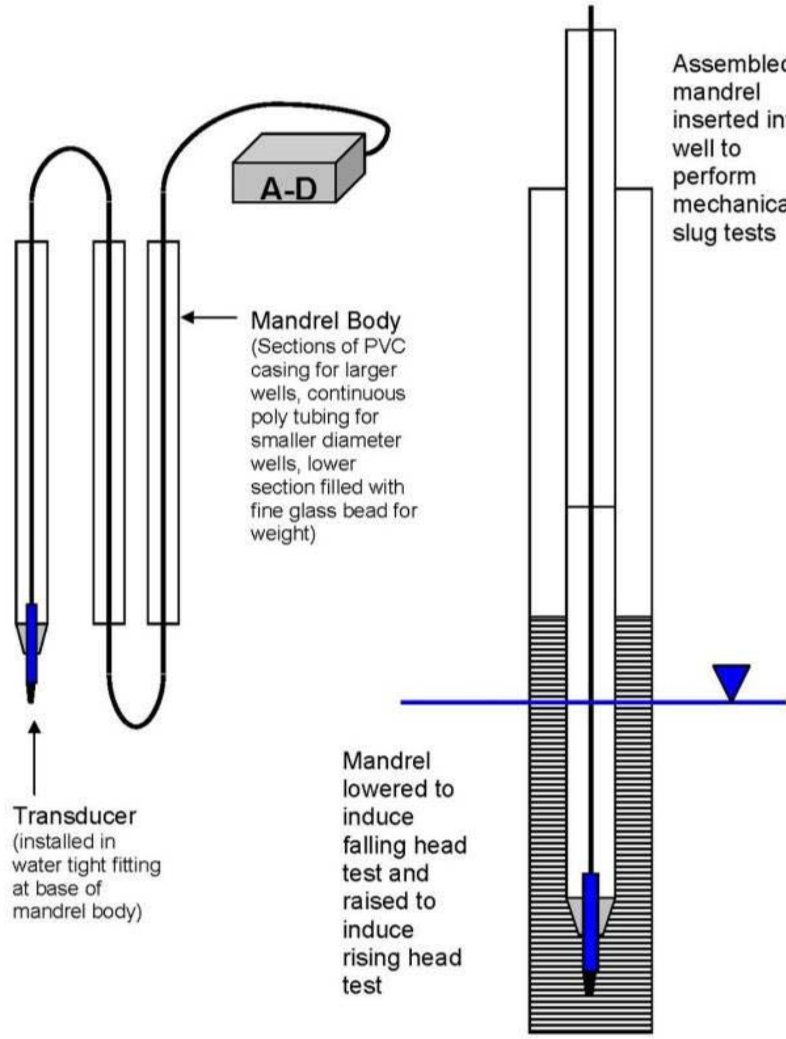



Figure 7. Figure of the mandrel system for mechanical slug tests.

*Field quality control*

As mentioned previously, the field team typically performed three tests with the $H_o$ equal to ~20 in. of water displacement. The field team also performed replicate tests with different initial head values when time and conditions permitted. These replicate tests allowed the field team to determine if the wells were adequately developed or needed redevelopment due to silting in or biofouling. Visual inspection was used to evaluate if the peak height and recovery curve symmetry were similar for the replicate tests. Good repeatability of the test results for similar $H_o$ indicated that the well was adequately developed and was responding appropriately for slug-test modeling. Conversely, significant changes in peak height or recovery curve symmetry indicated that well redevelopment was needed. Only a few wells used in this study required redevelopment.

## Well redevelopment

There were only a few wells where replicate tests (with similar $H_o$) showed significant changes in either peak height or recovery curve symmetry. When this occurred, the well was redeveloped in an attempt to obtain useable slug-test data. Development was done by manually surging and purging the well in a manner that was consistent with industry practices as given by ASTM D5521 and by Kraemer et al. (2006). An inertial-lift pump was used to surge and purge the well and was constructed using a check valve, check ball, and poly-tubing (Figure 8).

In all, three wells needed to be redeveloped. All were CPT wells at Hanscom AFB. Two of these wells apparently were poorly constructed as they could not be redeveloped (i.e., abundant sediment coming in the screens). This may have resulted from improper sizing of the screen slot relative to formation grain size or possibly due to screen damage that occurred during installation.

Figure 8. Equipment used to redevelop wells, including small check valve, check ball, and poly-tubing used to redevelop smaller DP wells.

## Slug-test responses, data modeling, and analyses

The response curves from the slug tests were modeled to calculate the hydraulic conductivity of the screened formation. Available geologic information for each facility (Appendix B) indicated that all of the wells were installed in unconfined aquifer conditions. So, the over-damped well responses were modeled with the Bouwer and Rice (1976) method. More recently, modifications to this model have been made to allow for its application to under-damped well responses (Butler et al. 2003). The modified

Bouwer and Rice model was applied to under-damped slug-test responses observed from wells included in this study.

The Slug Test Analysis software package (Geoprobe 2005) was used to model both the over-damped and under-damped slug-test results and to calculate the hydraulic conductivity using the appropriate analytical method (as discussed previously). All slug-test recovery curves were modeled as partially penetrating wells installed in unconfined aquifers. This procedure was consistent with available hydrogeologic information for each facility and well construction data.

To evaluate the potential for water column acceleration effects on some of the fast recovering under-damped slug-test responses, an Excel spread sheet was prepared. The potential for acceleration effects were greatest in wells where a pneumatic packer was used with the small nominal 1/2-in. riser. The spreadsheet was designed initially to model under-damped responses in a method similar to that of Butler et al. (2003). This spread sheet was modified to enable modeling for the acceleration effects of the water column on pressure transducer readings during under-damped slug tests. Modifications for the analysis of the acceleration effects of the water column were based on publications of Zurbuchen et al. (2002) and Butler et al. (2003). The model curves for acceleration effects did not provide an improved model fit when compared to the standard under-damped model curves. In most cases, the modulations of the acceleration model curves were out of phase with the field data. This may have been due to the very short water columns in these shallow wells. Therefore, the standard under-damped model curves were applied where reasonable fit with field data was achieved.

When plotting and analyzing the slug-test data for the wells at Dover AFB, it was apparent that several of the response curves displayed the characteristic “double-straight-line” effect (Bouwer 1989; Butler 1997) as shown in Figure 9. This appeared to be most common in the CPT-installed (no-pack) DP wells. Normalized plots of these responses displayed an initial response with a steep slope followed by a lower slope. The response (with the steeper slope) is believed to result from rapid recharge of the well from the filter pack surrounding the well screen in unconfined formations (Bouwer 1989). The later response, with the lower slope, is believed to represent the true aquifer recharge. Therefore, the early-time data was disregarded, and the later data was used to determine the hydraulic

conductivity of the formation. As an example, this was true for a 3/4-in. DP well, located Dover AFB (Figure 9).

As noted, an initial rapid recovery is usually regarded as recharge from the filter pack. At Dover AFB, the DP wells were installed without a filter pack in most of the cases. In these situations it is possible that a void area or zone of low-density formation collapse around the no-pack screen was the source of the early time rapid recharge.

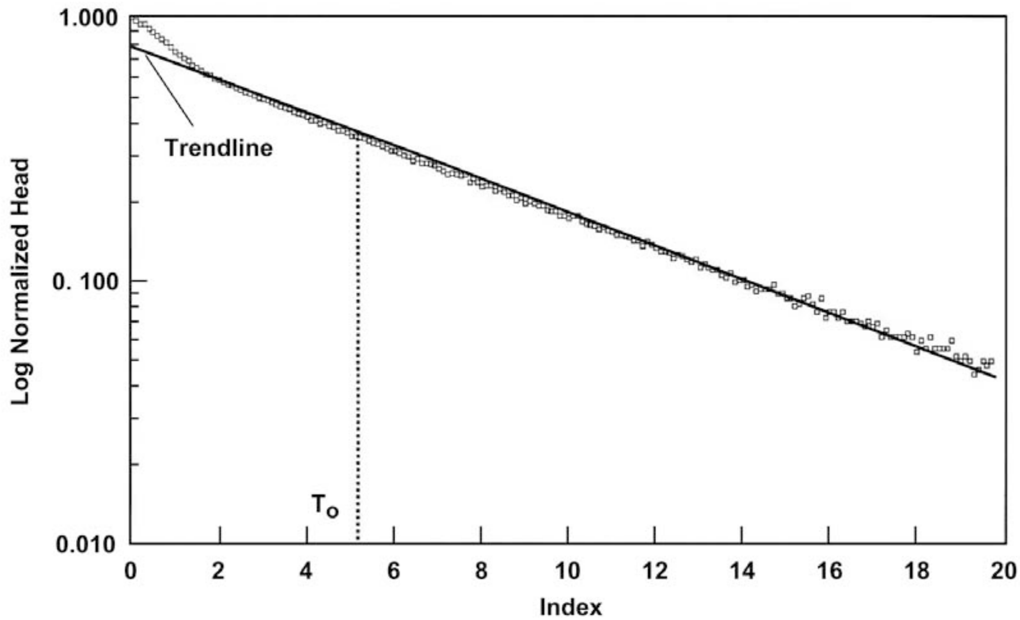



Figure 9. Slug-test results at Dover AFB display a characteristic "double-straight-line" effect. Notice the initial steeper slope that is not used to calculate the K value.

## Anomalous results and wells not tested

For the small diameter wells (1.0- to 0.5-in. nominal ID) screened across the water table, a packer system was not available that would allow for pneumatic slug testing. For these wells, mandrel tests were performed. Some of these wells produced very rapid responses to mandrel tests that were anomalous in symmetry and form. These anomalous tests could not be modeled with available methods or theories. Therefore, slug-test modeling and calculation of K could not be performed at these wells. Table 2 lists information on the wells that were not slug tested and those that provided anomalous responses or results.

Table 2. Wells that were not slug tested or did not yield appropriate test response.

| Facility | Well Number | Screen Length (ft) | Casing Nominal ID (in.) | Category (see below) |
|---|---|---|---|---|
| Tyndall AFB | MW 01 (½-in. DP) | 10 | 0.5 | 1 |
| | MWD 09 (1-in. DP[2]) | 25 | 1.0 | 2 |
| | MWD 09 (½-in. DP) | 25 | 0.5 | 1 |
| | MWD 11 (1-in. DP) | 25 | 1.0 | 1 |
| | MWD 11 (½-in. DP) | 25 | 0.5 | 1 |
| | T6-5 (½-in. DP) | 15 | 0.5 | 1 |
| Dover AFB | DMS337S (2-in. CPT[3]) | 10 | 2.0 | 3 |
| Hanscom AFB | RAP2-45 (CPT & conv.) | 10? | 2.0 | 4 |
| | OW2-2 | 10? | 2.0 | 4 |
| | OW2-6 | 10? | 2.0 | 5 |
| | RAP2-2T | 15? | 2.0 | 4 |

1. Anomalous slug tests could not be modeled; K values could not be calculated for these wells.
2. Limited number of tests could be modeled; some K values calculated.
3. Drop pipe tests attempted; did not yield results that could be modeled.
4. CPT well screen measured shorter than HSA well. Possibly screened over different intervals. Not tested as not representative of same screen interval or section of the aquifer. Possible screen collapse at OW2-2.
5. Well non-responsive to repeated attempts to slug test. Possibly plugged screen or extremely slow recovery. Insufficient time to test.

## Data analyses

### Precision of replicate tests

To determine the precision of the replicate slug tests, the Relative Standard Deviation (RSD) of the K values for each set of replicate slug tests was determined according to the following formula and is expressed as a percent:

$$RSD = (Standard\ Deviation/\ Mean)*100.$$

### Tests for the significance of well type, test type, and cluster location

In all cases, SigmaStat® software (by Systat Software, Inc., Point Richmond, CA) was used for the statistical analyses.

The data for each of the test sites were analyzed separately. For the data at the CRREL, Hanscom, and Dover test sites, a standard 3-way ANOVA test was conducted on the K values to determine the significance of well type (DP well vs. conventional well), test type (i.e., falling-head vs. rising-head

tests), and location of the well clusters or well pairs. In cases where the data did not meet the qualifications with respect to homogeneity of the variances and normality of the data set, the data were log transformed and then the 3-way ANOVA test was used. In instances where there were significant effects or interactions, a Holm-Sidak Multiple Comparison test was then used to determine which treatments differed from each other.

For the Tyndall site, considerably less data were available for the two smaller DP wells. Therefore, similar 3-way ANOVA tests were conducted on three data sets; the largest data set contained data only for the (1.5-in.) CPT and (2-in.) HSA wells, another contained data only for the 1-in. DP and (2-in.) HSA wells, and the third data set contained data for the 1/2-in. DP and HSA wells.

### Tests of duplicate well data

At two of the test sites, there were duplicate wells at some of the well clusters or well pairs. At Dover AFB, there were two duplicate HSA wells, two duplicate 3/4-in. DP wells, and one duplicate CPT well. For each well type, a standard paired t-test was used to determine if there was a statistically significant difference between the K value for the original wells vs. the duplicate wells, assuming that the data met the requisite tests for normality of the data set and homogeneity of the variances. In cases where the data did not meet these criteria, they were transformed using a natural log (ln) function. If the data then met these criteria, a paired t-test was performed on the ln-transformed data. In instances where neither the raw data nor the ln-transformed data met these criteria, a Wilcoxon Signed-Rank test was used. For these tests, the data were paired in such a fashion that the $H_o$ values were the same for the two wells being compared (i.e., the original and duplicate wells).

For the one replicate well at Tyndall AFB (a CPT well), a 2-way ANOVA was used to test the difference of test type (rising-head vs. falling-head) and well location within the cluster (i.e., original vs. duplicate). A paired t-test was also used to compare the K values for the new vs. the old CPT well.

# 3 Results and Discussion

## CRREL field site

At the CRREL site, the hydraulic conductivities from two different diameter pre-pack DP wells (1/2-in. and 3/4-in. ID) were compared with the K values from 4-in.-diameter conventionally installed HSA wells (well configurations are detailed in Table C-1 in Appendix C). The pre-pack DP wells were installed using percussion probing. All test data can be found in Table C-2 and are summarized in Table 3. The mean K values ranged from 0.4 to 8.0 ft/day for these wells.

Table 4 summarizes the precision of the replicate slug tests. Test results are detailed in Table C-3. Generally, the reproducibility of the replicate slug tests was excellent (i.e., the percent RSD for the replicates was less than 10% in all but one case). An example of the repeatability of the slug tests is shown in Figures 10a and 10b for MW 09. Figures 10c and 10d show the agreement between the test results for slug tests with different values of $H_o$ in the same well. As mentioned previously, the precision of the slug tests is a function of the well design, formation conditions, and the adequacy of prior well development. The generally good agreement between these replicate tests indicated that these wells did not need redevelopment.

Table 3. Summary of slug-test results at CRREL.

| Cluster | Well type | Mean K (ft/d) | | | |
|---|---|---|---|---|---|
| | | Rising-head test | Falling-head test | All data [1] | Equal weighted [2] |
| 9 | ¾-in. DP | 2.19 | 3.87 | 3.11 | 3.03 |
| | 4-in. HSA | 4.30 | 4.40 | 4.34 | 4.35 |
| | ½-in. DP | 3.48 | 2.53 | 3.00 | 3.00 |
| 10 | ¾-in. DP | 8.16 | 7.92 | 8.05 | 8.04 |
| | 4-in. HSA | 2.55 | 2.74 | 2.65 | 2.65 |
| | ½-in. DP | 6.44 | 5.38 | 5.98 | 5.91 |
| 11 | ¾-in. DP | 2.09 | 1.96 | 2.02 | 2.02 |
| | 4-in. HSA | 0.98 | 1.13 | 1.04 | 1.05 |
| | ½-in. DP | 0.48 | 0.43 | 0.45 | 0.45 |

[1] Simple mean of all data

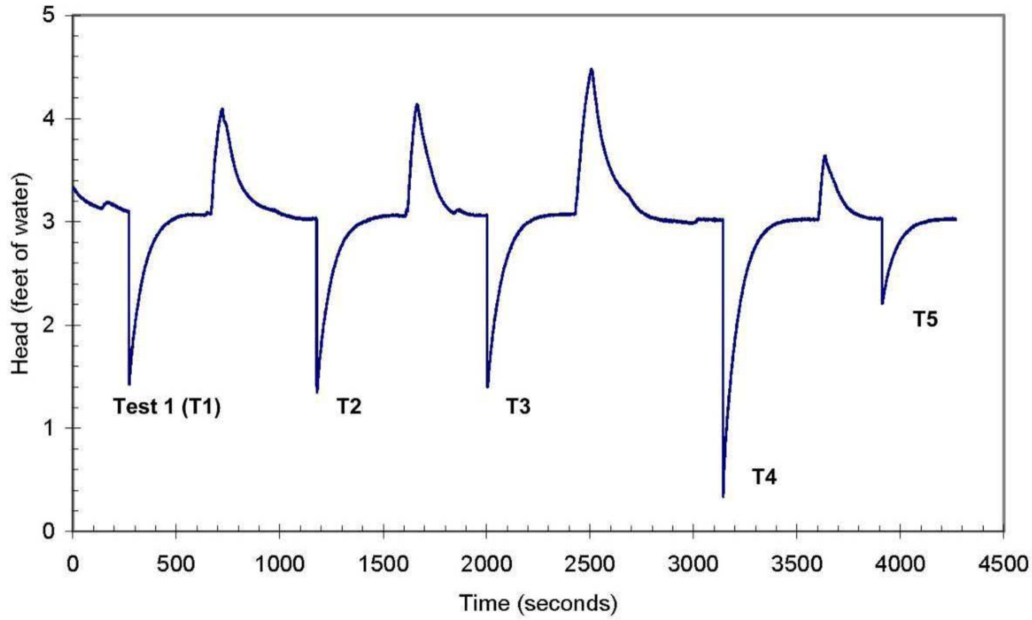
[2] Equal weighted mean = (mean $K_{\text{rising-head test}}$ + mean $K_{\text{falling-head test}}$)/2

Table 4. Summary of findings for replicate slug tests at CRREL site.

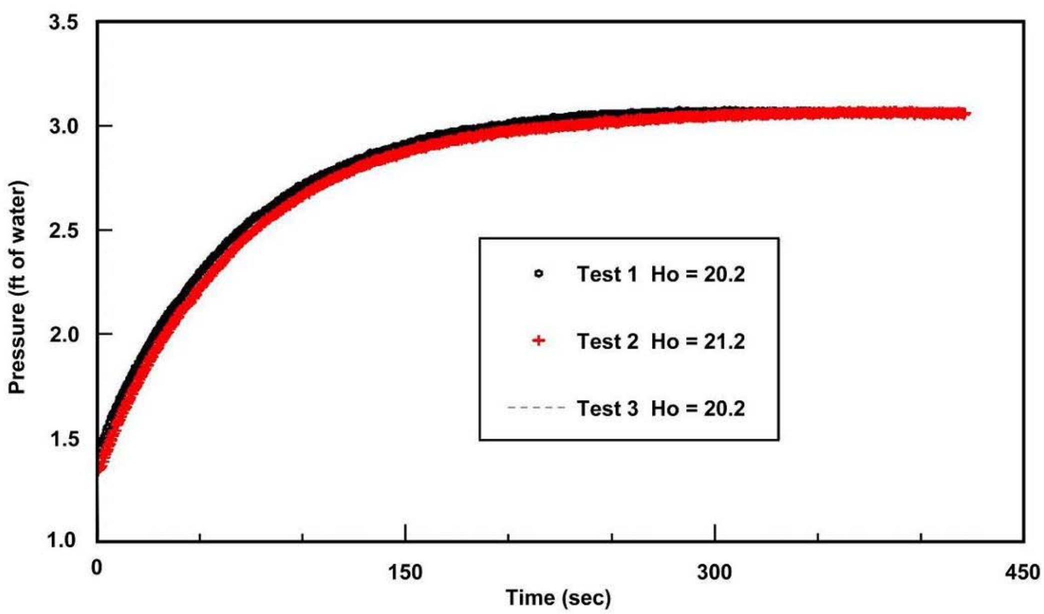
| Cluster | Well type | RSD (%) | |
|---|---|---|---|
| | | Rising-head | Falling-head |
| 9 | ¾-in. DP | 3.2 | 16 |
| | ½-in. DP | 2.2 | 3.0 |
| | HSA | 2.9 | 6.0 |
| 10 | ¾-in. DP | 9.5 | 0.03 |
| | ½-in. DP | 2.2 | 1.1 |
| | HSA | 7.8 | 2.9 |
| 11 | ¾-in. DP | 4.7 | 4.0 |
| | ½-in. DP | 2.4 | 1.4 |
| | HSA | 6.0 | N/A |

Generally, there was reasonably good agreement between the rising-head tests and the falling-head tests (Table 3), especially when one considers the range of values found in nature where hydraulic conductivity ranges over more than 10 orders of magnitude (Butler 1997). Statistical analyses (ANOVA) revealed no statistically significant difference could be associated with test type (i.e., falling-head vs. rising-head tests). The statistical analyses also revealed a significant interaction between well type and location. That is, at some clusters (i.e., location), the conventional well yielded significantly higher K values than the DP wells; at other clusters, the opposite was true (Table 3). This interaction can be easily seen by examining Figure 11.

The results for the HSA wells also agreed reasonably well with the values previously reported in the Remediation Investigation Report (Arthur D. Little 1994), as shown in Table 5.




**10a. Plot of the rising-head five-test series.** The first three tests had $H_o$ values of ~20 in. of water displacement. The fourth and fifth tests had $H_o$ values of ~31 and 10 in. of water displacement, respectively.




**10b. Three replicate slug tests with a $H_o$ of ~20 in. (not normalized).** Close agreement between these results shows the excellent repeatability of these tests.

Figure 10. Results of the rising-head tests at CRREL site at MW 09.

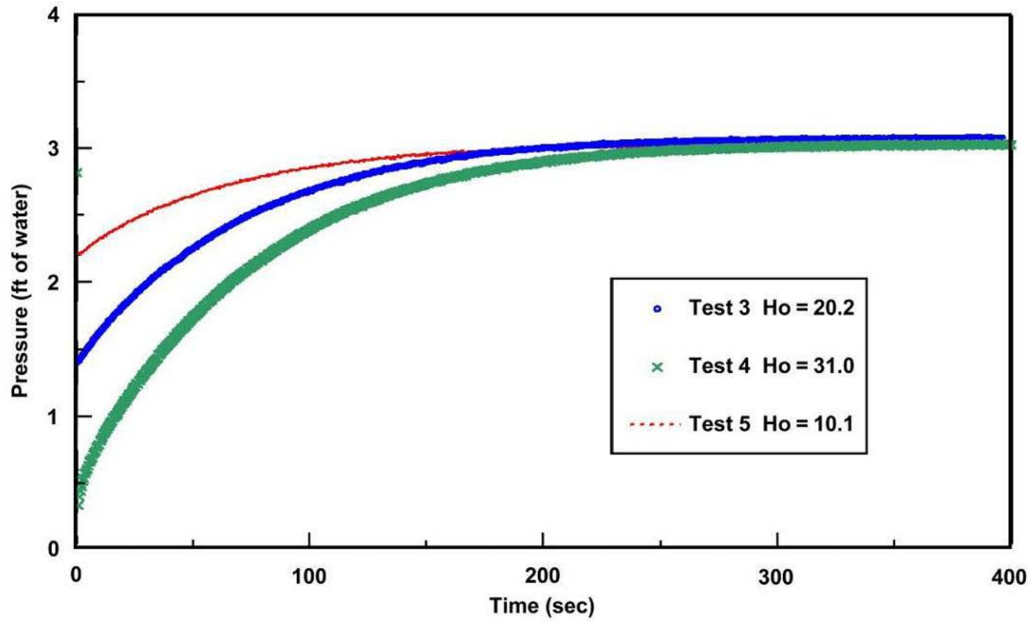



**Figure 10c. Results of three slug tests with different Ho values.** This non-normalized plot demonstrates the well/aquifer system responded to the different Ho values appropriately, with proportionally increasing displacement and symmetrical recovery curves.

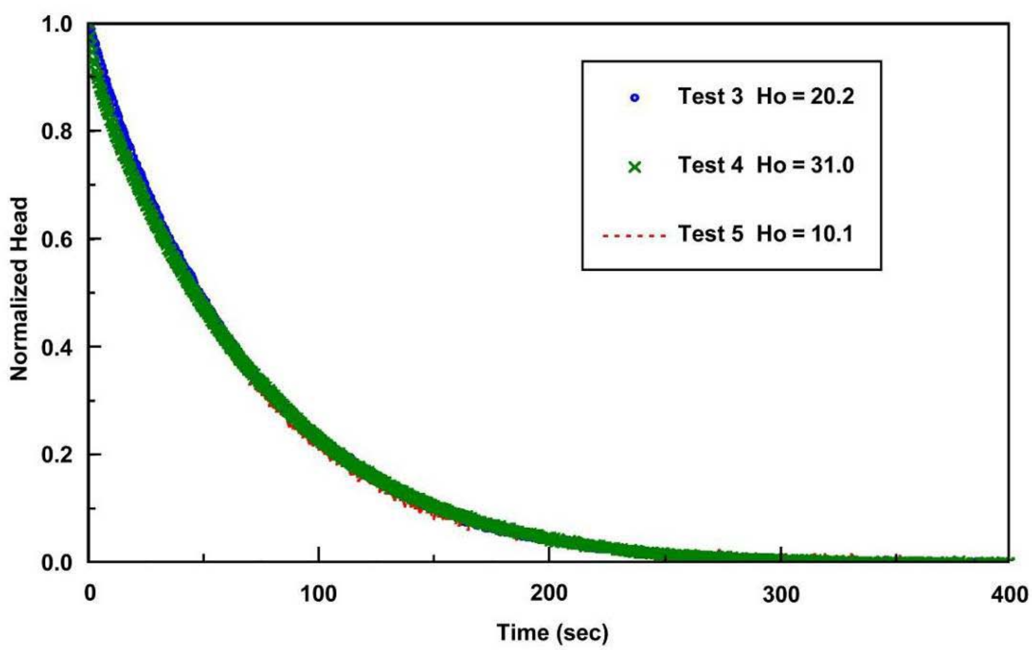



**Figure 10d. Normalized plots of the three slug tests with different Ho values.** The close correlation of the normalized plots demonstrates that the well/aquifer system responds linearly over the range of head values used to initiate the tests and as such conventional modeling theory was applicable.

**Figure 10 (Cont'd). Results of the rising-head tests at CRREL site at MW 09.**

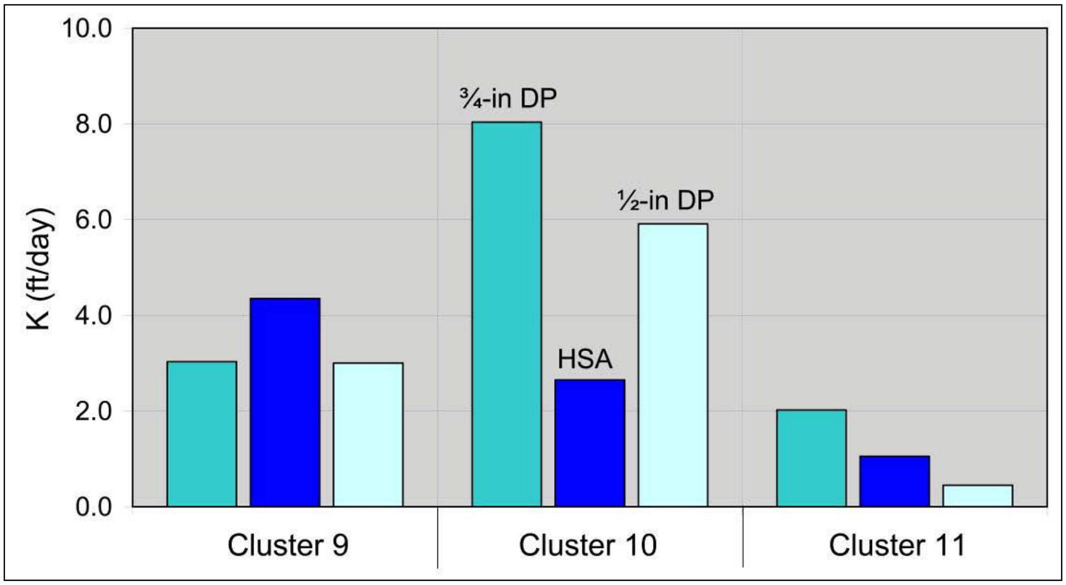



Figure 11. Mean K values for wells at CRREL.

Table 5. Comparison between current and previous slug-test results in 4-in. HSA wells at CRREL.

| Well Number | Previous Results[1] K (ft/d) | | Current Results K (ft/d) | |
|---|---|---|---|---|
| | Rising-head | Falling-head | Rising-head | Falling-head |
| MW 09 | 16.2 | 4.79 | 4.30 | 4.40 |
| MW 10 | 1.21 | 2.35 | 2.55 | 2.74 |
| MW 11 | 0.126 | 0.165 | 0.98 | 1.13 |

[1] (Arthur D. Little 1994)
Values converted from ft/sec to ft/d (by multiplying by 86,400).

## Hanscom AFB

At the Hanscom AFB test site, hydraulic conductivity values determined for the 2-in.-diameter HSA wells were compared with those of the 2-in.-diameter CPT DP wells. Five well pairs were compared (Table C-4). The CPT wells were installed using a quasi-static installation method. Table C-5 gives the results from all of the slug tests and Table 6 summarizes that data. The mean K values ranged from 0.7 to 41 ft/day at this site.

Table 7 summarizes the precision of the replicate slug tests. Test results are detailed in Table C-6. Generally, the reproducibility of the replicate slug tests was good. The RSD was less than 10% for most replicate tests (19 out of 22) and was less than 16% for all the replicate tests.

Table 6. Summary of slug-test findings at Hanscom AFB.

| Cluster | Rising-head test | | | Falling-head test | | | Combined | |
|---|---|---|---|---|---|---|---|---|
| | Slug type [1] | Mean K (ft/d) | | Slug type | Mean K (ft/d) | | Mean K (ft/d) | |
| | | HSA well | CPT well | | HSA well | CPT well | All data | Equal-weighted |
| MWZ 11 | PN | 0.88 | 0.56 | PA/PN | 0.86 | 0.58 | 0.73 | 0.72 |
| MWZ6 | PN [2] | 0.56 | 0.66 | PA/PN | 1.82 | 0.47 | 0.77 | 0.88 |
| B107 | MN | 22.8 | 10.61 | MN | 25.5 | 13.9 | 19.6 | 18.2 |
| OW2-6 | MN | 2.68 | 3.71 | MN | 3.98 | 4.25 | 3.72 | 3.65 |
| RFW11 | MN | 31.1 | 48.4 | MN | 32.6 | 51.7 | 40.1 | 40.9 |

[1] PN = pneumatic test on casing; PA/PN = pneumatic test with packer; MN = 1-in. mandrel

[2] Upward concave normalized plots, especially for the falling-head tests. This may indicate a possible bias.

Table 7. Summary of the precision of the replicate slug tests at Hanscom AFB.

| Cluster | Rising-head tests | | | | | Falling-head tests | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Slug type [1] | HSA well | | CPT well | | Slug type | HSA well | | CPT well | |
| | | Mean $H_o$ (in.) | RSD (%) | Mean $H_o$ (in.) | RSD (%) | | Mean $H_o$ (in.) | RSD (%) | Mean $H_o$ (in.) | RSD (%) |
| MWZ 11 | PN | 19.3 | 11.6 | 10.3 | 2.2 | PA/PN | | | | |
| MWZ6 | PN [2] | 22.5 | 15.6 | 11.3 | 10.7 | PA/PN | | | 19.7 | 8.1 |
| B107 | MN | 21.5 | 5.5 | 21.9 | 2 | MN | 24.5 | 8.7 | 23.8 | 1.8 |
| | | 10.5 | 2.1 | | | | 12.5 | 0.7 | 11.9 | 8.6 |
| | | 32.2 | 9.5 | | | | 36 | 2.9 | | |
| OW2-6 | MN | | | | | MN | 24.5 | 4.8 | 24 | 4.6 |
| RFW11 | MN | 24.6 | 5.5 | 23.8 | 3.7 | MN | 24.6 | 4.9 | 24.8 | 6.5 |
| | | 12.4 | 7.6 | | | | 11.8 | 6.3 | 12 | 7.1 |

[1] PN = pneumatic test on casing; PA/PN = pneumatic test with packer; MN = 1-in. mandrel

[2] Upward concave normalized plots, especially for the falling-head tests. This may indicate a possible bias.

Again, the good reproducibility that we found among these slug tests was an indication that these wells did not need redevelopment. However, it is interesting that the largest variability was with the pneumatic tests conducted on the well casing (with no packer) and that the RSD was less than 10% for the mandrel and the pneumatic tests conducted with a packer.

Statistical analyses of this data set revealed that the test type (i.e., falling-head vs. rising-head tests) had a significant impact on the K values at only two of the five well pairs, B107 and RFW11 (Table 6). However, there was no consistent trend associated with the test type. That is, the rising-head

test was higher for the RFW11, while the falling-head test was higher for B107.

The statistical analyses also revealed that there was significant interaction between location and well type. This means that, for some well pairs, the CPT well yielded a higher K value while, at other locations, the conventional wells yielded a higher K value. This result is illustrated in Figure 12, which shows the mean K values for each well type. Again, the only two well locations where there was a statistically significant difference between the CPT and the HSA wells were B107 and RFW11. For B107, the conventional well yielded a higher K value than the CPT well. While for the RFW11 wells, the opposite was true.

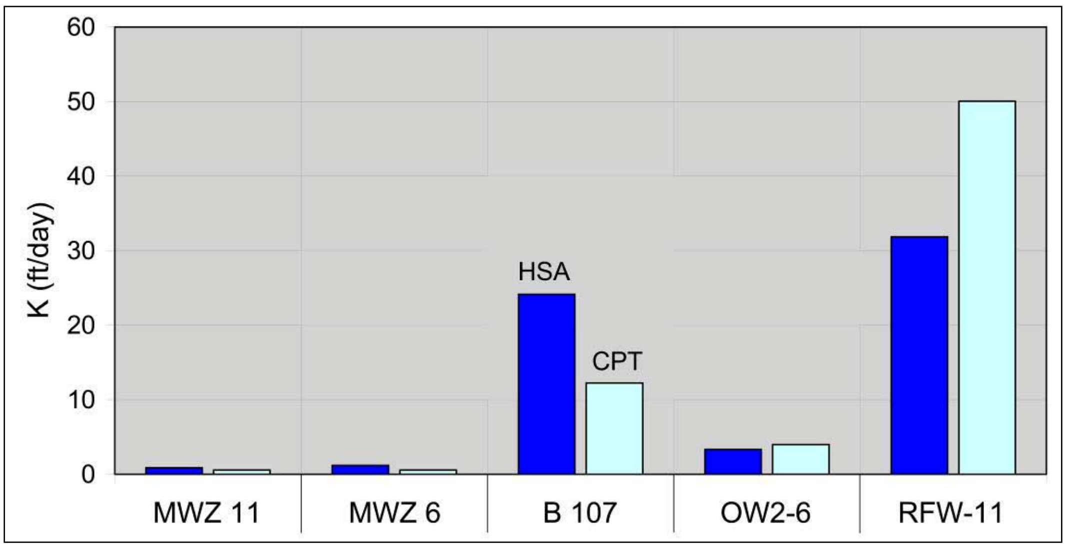



Figure 12. Mean K values for wells at Hanscom AFB.

## Dover AFB

At the Dover test site, there were 2-in.-diameter CPT-installed (with no pre-pack filter) DP wells and 2-in.-diameter HSA wells at four locations. The CPT wells were installed using a quasi-static installation method. At two clusters, 235D and 236D, there were additional wells. At both of these locations, there was a second (duplicate) 2-in.-diameter HSA well and a 3/4-in.-diameter pre-pack DP well. Cluster 236D had an additional duplicate 3/4-in.-diameter pre-pack DP well (Tables 8 and C-7). The 3/4-in.-diameter pre-pack DP wells were installed using percussion probing. All the test results for this site can be found in Table C-8 and are summarized in Table 9. The mean K values at this site ranged from 0.4 to 54 ft/day.

Table 8. Test wells at Dover AFB.

| Cluster | 2-in. HSA well | Duplicate HSA well | 2-in. CPT well | Duplicate 2-in. CPT well | ¾-in. DP well | Duplicate ¾-in. DP well |
|---|---|---|---|---|---|---|
| 53S | x | | x | | | |
| 235D | x | x | x | x | x | |
| 236D | x | x | x | | x | x |
| 237S | x | | x | | | |

Table 9. Summary of slug-test results conducted at Dover AFB.

| Cluster | Well type | Slug Type | Mean K (ft/d) | | Well type | Slug Type | Mean K (ft/d) | | Well type | Slug Type | Mean K (ft/d) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | FH | RH | | | FH | RH | | | FH | RH |
| 235 | 2-in. CPT | PN | 11.6 | 9.9 | 2-in. HSA | PN | 29.7 | 29.4 | ¾-in. DP | PN | 12.8 | 8.1 |
| | DW | PN | 16.1 | 15.0 | DW | PN | 16.1 | 15.0 | DW | PN | 3.6 | 3.0 |
| | DW | PA/PN | — | 2.44 | | | | | | | | |
| 236 | 2-in. CPT | PN | 53.1 | 55.4 | 2-in. HSA | PN | 3.67 | 4.91 | ¾-in. DP | PN | 1.40 | 1.99 |
| | | | | | DW | PN | 1.73 | 2.26 | DW | PN | 1.44 | 3.30 |
| 237S | 2-in. CPT | PA/PN | 2.44 | 2.23 | 2-in. HSA | PA/PN | 0.44 | 0.48 | | | | |
| 53S | 2-in. CPT | PA/PN | 9.08 | 9.07 | 2-in. HSA | PA/PN | 1.40 | 1.23 | | | | |
| FH = Falling-head test; RH = Rising-head test; DW = Duplicate well; PN = Pneumatic test; PA/PN = Pneumatic test with packer | | | | | | | | | | | | |

Table 10 summarizes the precision of the replicate slug tests for the older wells at Dover, and Table 11 summarizes for the newer replicate wells. Detailed data can be found in Tables C-9 and C-10.The reproducibility of the replicate slug-test results was excellent, with the RSD generally less than 10%. For both the 2-in. HSA wells and the 2-in. CPT wells, the precision of the test results for the pneumatic slug tests was generally slightly better (i.e., 0.4 to 6.4% RSD) than that for the pneumatic slug tests conducted with a packer (3.4 to 11.4% RSD). Also, although the RSD for the replicate 3/4-in. DP wells were generally less than 10%, the RSD tended to be slightly higher than they were for the 2-in. CPT and HSA wells (i.e., the precision of these tests was not quite as good). Again, these data indicated that wells were adequately developed at the time these tests were conducted.

Given the range of K values found in nature, there was excellent agreement between the two test types (rising-head vs. falling-head tests, Table 8). Statistical analyses of all the data revealed that there was no statistically significant difference that could be associated with the test type. However, there was a significant interaction between the well type and location

(cluster); this means that the effect of well type on the K value varied from cluster to cluster. At three of the clusters, CPT-DP wells had higher K values (especially at cluster 236). At cluster 235, however, the mean K value for the CPT wells was less than those for the two HSA wells. The variability in the effect of well type on K value can be seen in Figure 13, which shows the mean results for the CPT wells compared with those for the HSA wells at each location.

Table 10. Summary of the replicate slug tests in the older wells at Dover AFB.

| Cluster | Test type | Slug Type | 2-in. CPT | | 2-in. HSA | | ¾-in. DP | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean $H_o$ (in.) | RSD (%) | Mean $H_o$ (in.) | RSD (%) | Mean $H_o$ (in.) | RSD (%) |
| 235 | RH | PN | 20.6 | 2.3 | 20.7 | 2.2 | 20.6 | 9.0 |
| | FH | PN | 9.5 | 3.9 | 10.0 | 0.2 | 11.0 | 27 |
| 236 | RH | PN | 22.6 | 0.4 | 19.1 | 6.4 | 19.4 | 5.2 |
| | FH | PN | 20.2 | 3.6 | 19.2 | 1.4 | 20.8 | 6.8 |
| 237S | RH | PA/PN | 10.0 | 6.0 | 11.5 | 4.7 | | |
| | FH | PA/PN | 10.0 | 9.0 | 10.9 | 7.2 | | |
| 53S | RH | PA/PN | 10.3 | 3.5 | 10.0 | 11.4 | | |
| | FH | PA/PN | 9.9 | 3.4 | 9.9 | 10.2 | | |

FH = Falling-head test; RH = Rising-head test;
PN = Pneumatic test; PA/PN = Pneumatic test with packer.

Table 11. Summary of replicate slug tests in new replicate wells at Dover AFB.

| Cluster | Test type | 2-in. CPT duplicate well | | | 2-in. HSA duplicate well | | | 3/4-in. DP duplicate well | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Slug Type | Mean $H_o$ (in.) | RSD (%) | Slug Type | Mean $H_o$ (in.) | RSD (%) | Slug Type | Mean $H_o$ (in.) | RSD (%) |
| 235 | RH | PA/PN | 21.1 | 1.8 | PN | 21.1 | 1.8 | PN | 20.2 | 8.8 |
| | FH | PA/PN | 10.1 | 3.0 | PN | 10.1 | 3.0 | PN | 19.6 | 6.4 |
| 236 | RH | | | | | | | PN | 19.0 | 7.6 |
| | FH | | | | | | | PN | 19.9 | 11.9 |

FH = Falling-head test; RH = Rising-head test;
PN = Pneumatic test; PA/PN = Pneumatic test with packer.

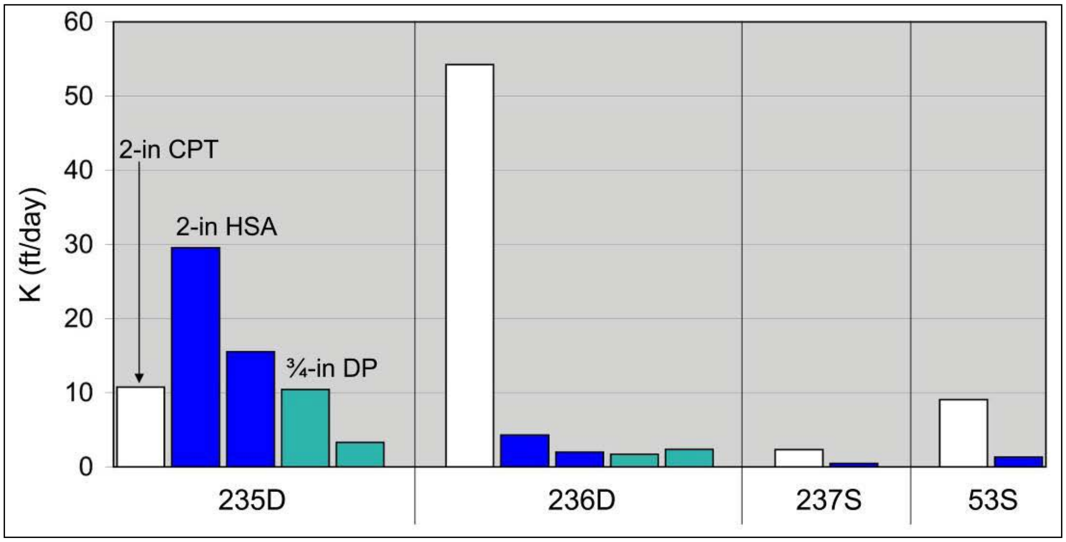



Figure 13. Mean K values for wells at Dover AFB.

Comparison between data for the duplicate wells and those for the original wells indicated the presence of a statistically significant difference between the K values of the older wells vs. the newer wells for both the CPT and the conventionally drilled wells. (The data were paired so that each comparison was for the same $H_0$ value.) However, these differences were not consistent for the two well types. For the replicate CPT well at site 235, the values were consistently greater in the newer wells (Table 9, Table C-8). In contrast, the K values for the older HSA wells (at sites 235 and 236) were almost twice the values for the newer wells (Table 9, Table C-8). For the replicate 3/4-in. DP wells (at clusters 235 and 236), there was no statistically significant difference between the K values of the newer and older wells. Again, these data demonstrate that the heterogeneity of the formation caused larger differences in the K values than the test method (i.e., rising-head vs. falling-head) or well type.

## Tyndall AFB

At Tyndall AFB, the K values from four different types of wells were compared at seven locations. At each location (well cluster), there was a conventional 2-in.-diameter HSA well, 1.5-in.-diameter CPT-installed DP well (with no pre-pack filter), a 1-in.-diameter pre-pack (Geoprobe) DP well, and a 1/2-in. pre-pack (Geoprobe) DP well. Also, there was a duplicate CPT well at cluster T6-5. The CPT wells were installed using a quasi-static installation method, and the 1-in. and 1/2-in. pre-pack DP wells were installed using percussion probing. As mentioned previously, the screen depth and length for the CPT and DP wells were matched as closely as

possible to the depth and length of the conventional HSA wells. The wells at clusters MW 01, MW 02, MW 05, and MW 08 had ~10-ft screens, cluster T6-5 had 15-ft screens, and the MWD 09 and MWD 11 clusters had ~25-ft screens (Table C-11). Generally, the same type of test was used whenever possible for all the wells at a particular cluster. However, this was not always possible because of the different well diameters.

Test data for this site are summarized in Table 12 and detailed in Table C-12 in Appendix C. The mean K values for this site were similar in range to the other three sites and ranged from 0.8 to 30 ft/day. The long-screened wells resulted in high transmissivity and extremely rapid responses to the mandrel tests. This produced anomalous slug-test responses that could not be modeled or analyzed with conventional theory or methods. These problems were more acute in the smaller diameter wells with long screen intervals (Tables 13 and 14).

Table 12. Summary of slug-test results at Tyndall AFB.

| | | Mean K (ft/d) | | | |
|---|---|---|---|---|---|
| Site | Well type | Rising-head | Falling-head | Overall | Equal wt. |
| MW 01 | HSA | 21.1 | 26.8 | 23.9 | 23.9 |
| | 1.5-in. CPT | 12.2 | 12.0 | 12.1 | 12.1 |
| | 1-in. DP | 21.1 | 13.1 | 17.1 | 17.1 |
| MW 02 | HSA | 22.8 | 23.8 | 23.2 | 23.3 |
| | 1.5-in. CPT | 27.8 | 32.2 | 27.8 | 30.0 |
| | 1-in. DP | 16.1 | 18.0 | 17.0 | 17.1 |
| | ½-in. DP | 9.6 | 12.8 | 10.8 | 11.2 |
| MW 05 | HSA | 2.5 | 2.3 | 2.4 | 2.4 |
| | 1.5-in. CPT | 0.7 | 0.8 | 0.8 | 0.8 |
| | 1-in. DP | 16.7 | 21.4 | 19.8 | 19.0 |
| | ½-in. DP | 0.7 | 2.4 | 0.9 | 1.5 |
| MW 08 | HSA | 2.2 | 2.2 | 2.2 | 2.2 |
| | 1.5-in. CPT | 6.2 | 6.9 | 6.5 | 6.5 |
| | 1-in. DP | 9.3 | 11.6 | 10.3 | 10.5 |
| | ½-in. DP | 1.8 | 2.0 | 1.8 | 1.9 |
| MWD 09 | HSA | 1.7 | 1.4 | 1.5 | 1.5 |
| | 1.5-in. CPT | 3.4 | 3.9 | 3.7 | 3.6 |
| | 1-in. DP | 0.9 | 0.8 | 0.8 | 0.8 |
| MWD 11 | HSA | 1.33 | 1.64 | 1.48 | 1.48 |
| T6-5 | HSA | 1.5 | 1.5 | 1.5 | 1.5 |
| | 1.5-in. CPT | 1.6 | 1.4 | 1.6 | 1.5 |
| | 1.5-in. CPT dup. | 1.9 | 2.0 | 1.9 | 1.9 |
| | 1-in. DP | 4.9 | 2.6 | 4.1 | 3.8 |

Table 13. Summary of precision of slug tests for 2-in. HSA and 1.5-in. CPT DP wells at Tyndall AFB.

| Cluster | 2-in. HSA Slug type | Test Type | Mean $H_o$ (in.) | RSD (%) | 1.5-in. CPT Slug type | Test Type | Mean $H_o$ (in.) | RSD (%) |
|---|---|---|---|---|---|---|---|---|
| MW 01 | 1-MN | RH | 5.8 | 34 | 1-MN | RH | 4.0 | 11 |
| | | FH | 5.2 | 20 | | FH | 3.2 | 30 |
| MW 02 | PN | RH | 19.1 | 3.6 | PN | RH | 15.8 | 1.4 |
| | 1-MN | RH | 17.4 | 6.1 | | | | |
| | | FH | 36.4 | 2.2 | | | | |
| MW 05 | PA/PN | RH | 19.7 | 17 | PA/PN | RH | 20.0 | 10 |
| | | FH | 19.9 | 4.1 | | FH | 20.0 | 8.3 |
| MW 08 | PA/PN | RH | 20.0 | 10 | 0.5-MN | RH | 12.1 | 11 |
| | | FH | 20.3 | 0.5 | | FH | 23.9 | 8.4 |
| MWD 09 | PA/PN | RH | 20.5 | 3.9 | PA/PN | RH | 20.5 | 0.0 |
| | | FH | 20.1 | 0 | | FH | 20.3 | 2.2 |
| | | | | | | FH | 10.4 | 2.4 |
| | | | | | PA/PN | RH | 20.0 | 0.0 |
| | | | | | | FH | 20.0 | 2.3 |
| MWD 11 | PA/PN | RH | 19.3 | 5.3 | | | | |
| | | FH | 20.1 | 7.5 | | | | |
| T6-5 | PA/PN | RH | 19.7 | 0 | PA/PN | RH | 20.0 | 0.0 |
| | | FH | 21.6 | 2 | | FH | 20.0 | 4.4 |
| | | | | | New 1.5-in. CPT | | | |
| | | | | | PA/PN | RH | 20.2 | 1.7 |
| | | | | | | FH | 20.1 | 5.3 |

FH = Falling-head test; RH = Rising-head test;
PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; 0.5-MN = 0.5-in. ID mandrel.

Table 14. Summary of precision of slug tests for the 1-in. and 0.5-in. DP wells at Tyndall AFB.

| Cluster | 1-in. DP Slug type | Test Type | Mean $H_o$ (in.) | RSD (%) | 0.5-in. DP Slug type | Test Type | Mean $H_o$ (in.) | RSD (%) |
|---|---|---|---|---|---|---|---|---|
| MW 02 | PN | RH | 20.6 | 8.6 | PN | RH | 18.8 | 2.4 |
| MW 05 | 12-MN | RH | 17.2 | 21 | BT | RH | 13.6 | 9.3 |
| | | FH | 13.5 | 11 | | | | |
| MW 08 | 12-MN | RH | 11.9 | 29 | BT | RH | 21.3 | 0 |
| | | RH | 10.4 | 2.3 | | | | |
| | | FH | 24.2 | 2.5 | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; 12-MN = 12-mm mandrel;
BT = Bare transducer.

Table 13 summarizes the precision of the replicate slug tests for the 2-in. HSA wells and the 1.5-in. CPT wells, and Table 14 summarizes for the smaller diameter (1/2-in. and 1-in.) DP wells. These data are detailed in Table C-13. The precision of the replicate slug tests in the same wells was

generally very good (with the RSD equal to 10% or less). However, there was more variability in some cases than has been seen at the other sites. Two test methods were used for the 1/2-in. DP wells: a pneumatic method in one well and a bare transducer in two other wells. For these wells, the reproducibility was excellent, with the RSD less than 10%.

The same was true for the pneumatic slug tests in the 1-in. DP wells. In contrast, the RSD was much more variable for the two (1-in. DP) wells at cluster numbers MW 05 and MW 08, where a mandrel was used.

For the 1.5-in. CPT wells, the RSD was generally 10% or less. The exceptions were for the MW 01 where a 1-in. mandrel was used and at MW 08 where a 1/2-in. mandrel was used.

For the 2-in. HSA wells, the RSD was again generally 10% or less. The most notable exceptions were for MW 01 where a 1-in. mandrel was used and MW 05 where a packer was used. It is interesting to note that all of the wells having a larger variance were wells with the shorter 10-ft screens. Bartlett et al. (2004) also saw the K values obtained from wells with 2-ft screens having more variability than those with 5-ft screens.

For both this study and Bartlett et al. (2004), initial head values ($H_o$) of approximately 10, 20, and 30 in. were used to induce the slug-test response for each well. For wells with shorter screens and smaller diameters, the same amount of energy was put into the well/aquifer system over a smaller zone for the same $H_o$ as compared to wells with a longer screen interval (and larger diameter). The same energy over a smaller zone would be more likely to induce movement of fines in the local formation and increase turbulent flow in the well/aquifer system. These effects could result in the greater variability of K measured in the shorter screened wells versus longer screened wells for the same $H_o$ value induced on the system. Other factors may influence the variability and additional research would be required to verify this hypothesis.

Clearly, the reproducibility of the slug tests was not as good in the wells where the mandrel method was used. This is to be expected given that moving the mandrel the desired distance quickly with minimal noise (to achieve the desired change in head) is generally less repeatable and typically introduces more noise in the slug-test recovery than the pneumatic method.

Statistical analyses that compared all the data from the CPT wells (and included different types of slug tests) and the HSA wells revealed that there was significant interaction between the test type (i.e., falling- vs. rising-head tests), well type, and location. This was also true when only the data from the pneumatic methods were compared. This interaction means that the affect of the testing methods varied with location and well type and that the effect of well type varied with location and test method.

When the 1-in.-diameter pre-pack DP wells were compared only with the HSA wells, the test type was not significant but again there was a significant interaction between well type and location, indicating that the effect of well type on the K value varied from cluster to cluster. A significant interaction was also found between the well type and location for the 1/2-in.-diameter pre-pack DP wells (only rising-head tests could be conducted in these wells). The lack of a trend associated with the well type can be seen in Figure 14. Clearly the heterogeneous nature of the soil/formation had a larger impact on K values than did the well construction method.

The impact of the heterogeneity of the formation on the K values was also demonstrated when the K values for the one replicate CPT well (at T6-5) were compared with the values for the original CPT well at the same cluster (Figure 14, Table 12). In this case, there was a statistically significant difference between the K values for the two CPT wells at the same well cluster.

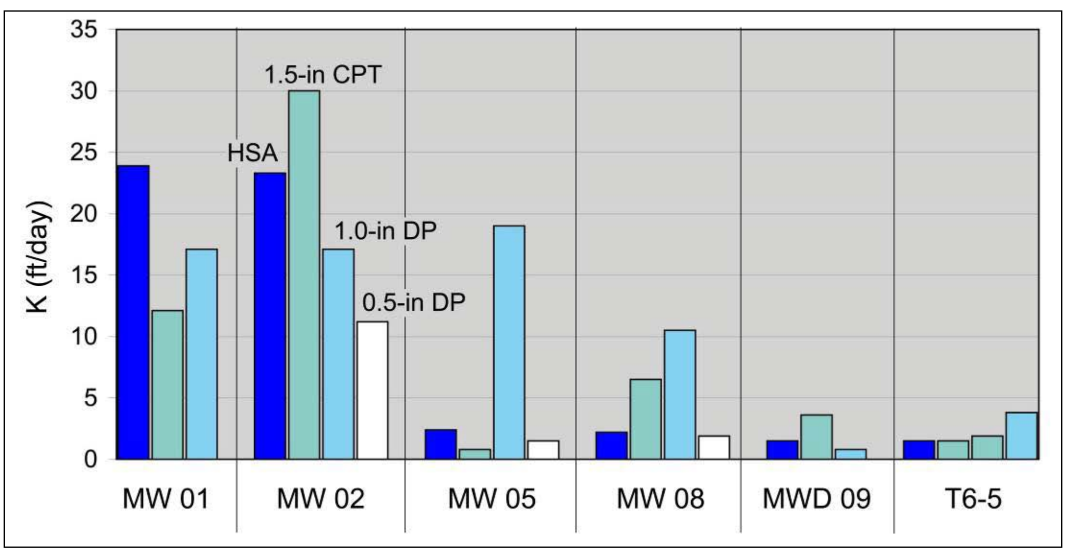



Figure 14. Mean K values for wells at Tyndall AFB.

These findings — that the heterogeneous nature of the formation had a larger impact on K values than did well construction method — agree with those of Bartlett et al. (2004) for the Port Hueneme site.

## General discussion of all sites

Generally, the replicate slug tests yielded results that agreed well. There did not appear to be any significant bias associated with well size but, in some cases, the tests that used a mandrel yielded slightly greater variability in the test results.

The range in the mean K values at these four sites was fairly similar from site to site, and the overall range in the mean K values for all four test sites was from 0.4 to 54 ft/day. Generally, there were no significant differences that could be attributed to test type (i.e., falling-head vs. rising-head). However, there was significant interaction between the location of the well clusters and the well type, indicating that the small-scale heterogeneity at each of the well clusters resulted in larger differences in the K values than did the well types. These findings indicate that similar K values can be obtained from DP wells when compared with the K values obtained from conventional HSA wells. We also noted, at both Dover AFB and Tyndall AFBs, that the slug tests with the smallest $H_0$ yielded the largest K value. However, the opposite (i.e., where the largest $H_0$ yielded the lowest K value) was not true at any of the sites.

It is interesting that several researchers (Butler 1997 and Sanchez-Villa et al. 1996) have observed that pumping tests generally result in higher K values than slug tests in the same aquifer. They attributed these differences to the difference in the scale of the two tests. (Pumping tests influence a larger volume of the aquifer than a single-well slug test.) If the effect of scale had been a significant factor in this study, it would have been expected that the larger conventional wells would have yielded higher K values more frequently than the much smaller DP wells at CRREL and at Tyndall. However, this was not the case. While some effect of scale between the different well sizes may exist, the small-scale heterogeneity of K in the aquifer systems studied was probably too large to allow this to be observed.

# 4 Conclusions and Recommendations

Generally the replicate slug tests yielded results that agreed well, with an RSD of 10% or less. There did not appear to be any significant bias associated with well size. In some cases, however, the mandrel slug tests yielded slightly greater variability in the test results. Given the manual nature of the mandrel method, this result is not unexpected.

At all four sites, small-scale formation heterogeneity had a significant impact on the variability of the slug-test results from the co-located wells. This heterogeneity had a larger effect on K values than the test type (i.e., rising-head vs. falling-head tests) or well construction method (i.e., HSA wells vs. pre-pack DP wells vs. CPT no-pack wells) or well diameter. Geologic settings at the sites ranged from glaciofluvial/glaciolacustrine at CRREL, to coastal plain deposits at Dover AFB and Tyndall AFB, and to lacustrine deposits over glacial till and granitic bedrock at Hanscom AFB. Soil types where the wells were screened generally varied from sandy silts to silty sand and some sand and gravel mixtures.

These findings agree well with those of Bartlett et al. (2004) who conducted a similar study at Port Hueneme, where the mean K value for the site was 57 ft/day (converted from 0.02 cm/sec).

Therefore, for formations where the K values range from a few tenths of a foot/day to ~60 ft/day, slug tests conducted in DP wells, including no-pack CPT wells and pre-pack DP wells as small as 1/2 in. in diameter, can yield comparable K values to those obtained using the conventionally installed HSA wells.

Our results also agree with those of several researchers (Sanchez-Villa et al. 1996; Bright et al. 2002; and Zheng and Gorelick 2003) who evaluated the effect of heterogeneity on transmissivity (transmissivity = K/aquifer thickness), solute transport, and contaminant transport prediction. In general, they found that small-scale heterogeneity, even at the decimeter scale, has a substantial impact on these hydrogeologic parameters.

Some general recommendations for field slug-testing methods are:

- Perform replicate tests with the same initial head to verify repeatability and evaluate well (re)development needs.
- Perform replicate tests with different initial head values to verify applicability of applied models and linearity over the range of head values selected.
- Review well construction before performing slug tests to determine the appropriate test methods.

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# Appendix A: Site Maps

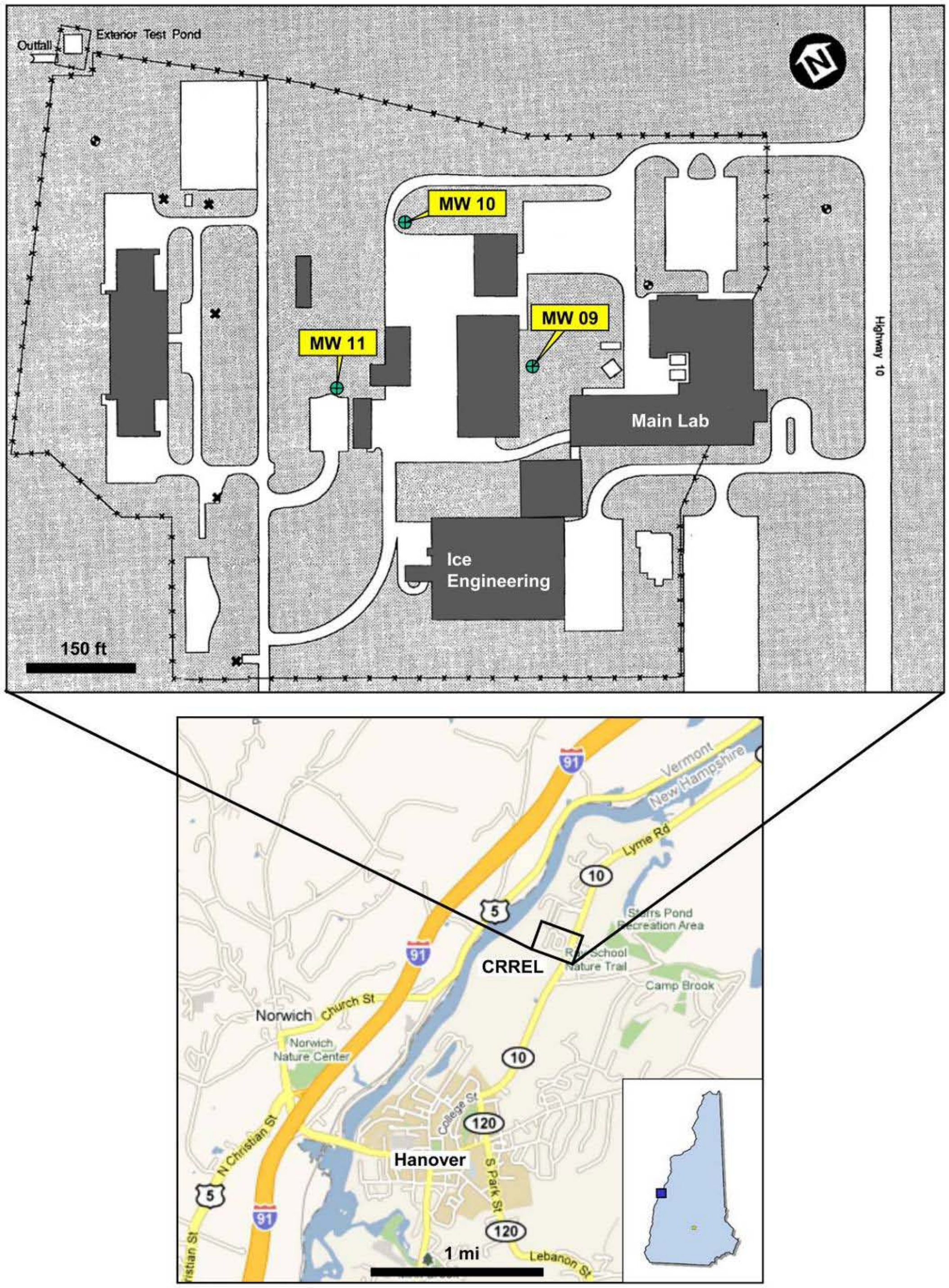


Figure A-1. Location of CRREL test site in west central NH, about 2 miles NNE of Hanover (lower) and site map of the tested wells within the CRREL campus (upper) (after Major et al. 2009).

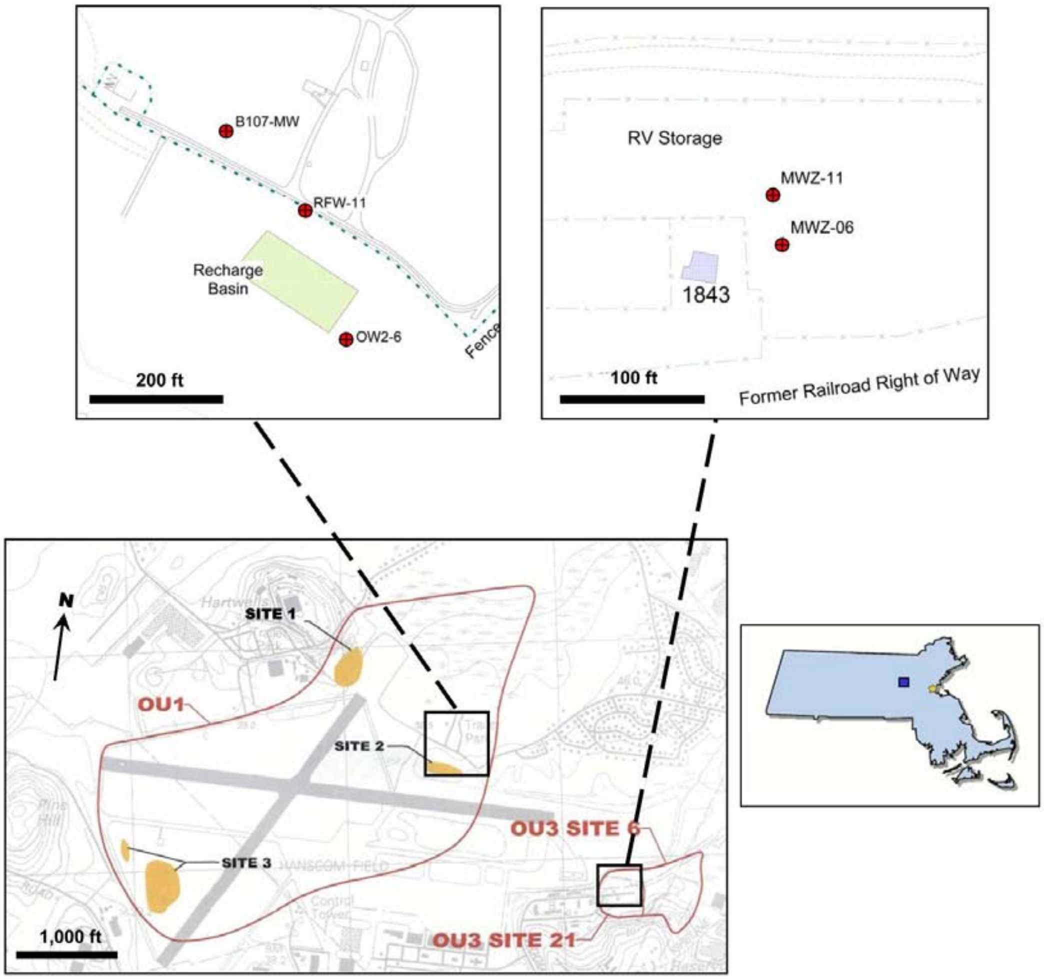


Figure A-2. Location of the Hanscom AFB test site in eastern central MA (lower) and site maps of the tested wells (upper).

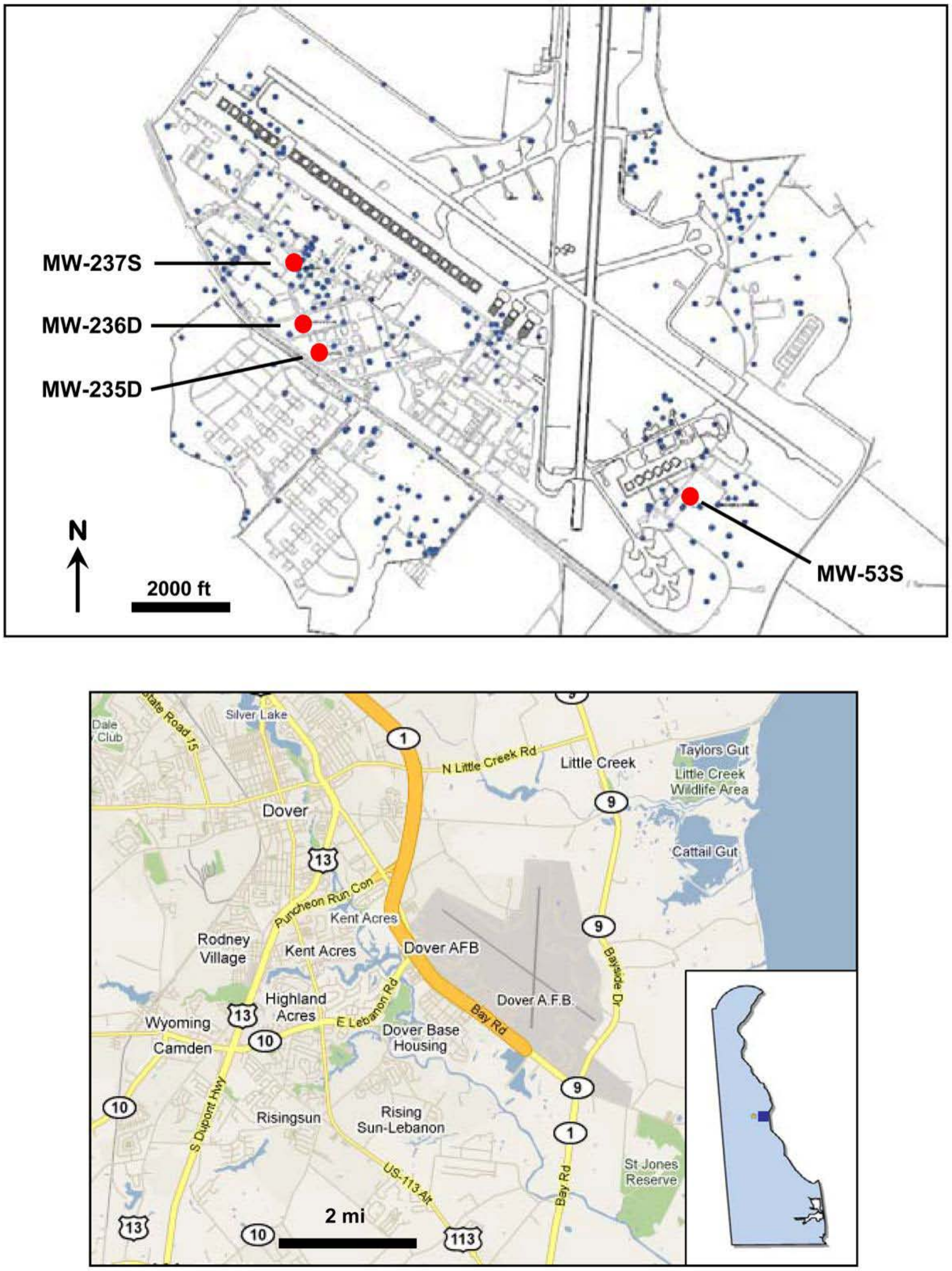


Figure A-3. Location of Dover National Test Site (lower) and position of the tested well clusters and pairs (upper).

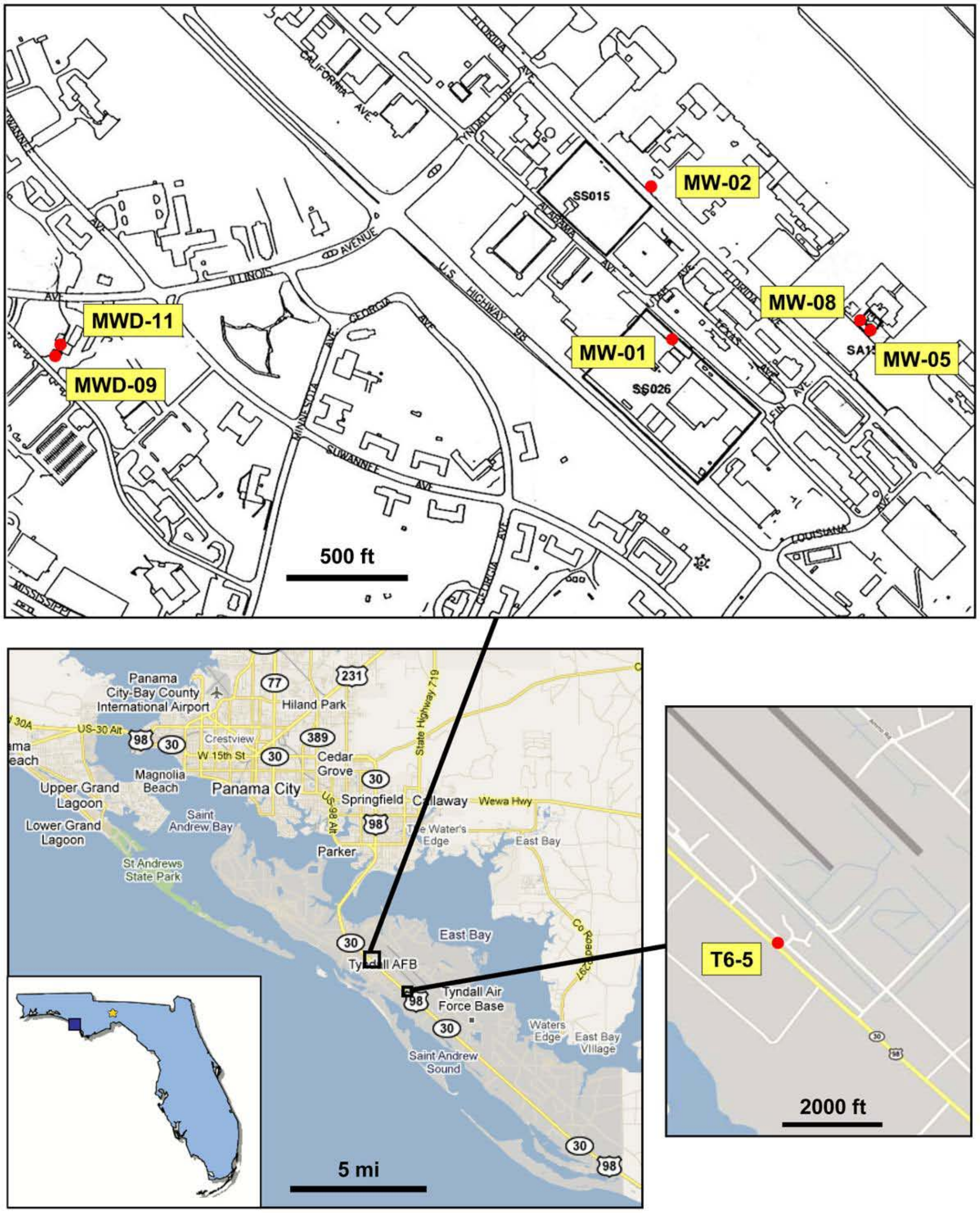


Figure A-4. Location of Tyndall AFB (lower left) and location of the tested wells.

# Appendix B: Site Geology and Hydrogeology

## CRREL site

### Geology

The CRREL campus is located on the east side of the Connecticut River valley in central western New Hampshire, within the New England physiographic province of the Appalachian Mountains (Hunt 1967) (Figure A-1). Underlying bands of metamorphic and igneous bedrock in this province have produced N-NE-trending ridges and valleys having relief locally of about 900 ft (Lyons 1955; Shoop and Gatto 1992). Bedrock beneath the site consists of deformed metasedimentary and rock (Lyons 1955). Available borehole and geophysical data indicate that the majority of the site is located on top of a buried asymmetric bedrock valley. Bedrock coring at five locations indicates that the bedrock beneath CRREL consists of amphibolite and paragneiss. Unconsolidated sediments 80- to 235-ft thick that overlie the bedrock have eroded into a stepped terrace topography (Arthur D. Little 1994). The sediments were deposited during two glacial advance and retreat cycles during the Wisconsin period, approximately 25,000 to 10,000 years ago (Stewart and MacClintock 1969).

Unconsolidated sediments at CRREL include two primary units – glaciofluvial and glaciolacustrine (Arthur D. Little 1994). A deep north-south trending glaciofluvial esker lies above the bedrock along the western boarder of the site. Eskers are deposits created by high-energy subglacial streams; therefore, their sediments include highly permeable fine- to coarse-grained sand (Unified Soil Classification SP and SW) with a few thin (~ 1-ft-thick) gravel layers. Younger surficial glaciolacustrine deposits overlie the esker to the west and the bedrock to the east. These sediments were deposited during the presence of a glacial lake (Lake Hitchcock) that formed when melt water from a retreating glacier was dammed by a moraine near Middletown, CT. The character of glaciolacustrine sediments is highly variable with grain sizes ranging from clay to fine sand and the layers from under an inch to several feet thick. The stratigraphy architecture indicates that the environment of the lake at this location evolved from a deltaic setting with a nearby sediment source (thicker-bedded fine sands) to a quieter setting at distance away from sediment input (varved, thin layers of silt and sandy silt).

Arthur D. Little (1994) divided the lacustrine sediment at this site into three main stratigraphic units. The basal unit is brown fine silty sand (SM) that, in places, is poorly sorted and frequently contains laminations of silt or layers of medium sand. The silty sand thickens eastward across the site from 20 ft to over 160 ft in depth, suggesting an eastern deltaic origin. The second unit, which overlies the SM and esker units, is olive gray to yellowish brown silt (ML) interbedded with layers of fine sandy silt. In general, the ML unit thickens from east to west (20 to 110 ft). The third lacustrine unit includes various layers of clay (CL) or silty clay that occur within both the SM and ML deposits. The clay lithologies are seen frequently in the ML deposit, ranging in thickness between 10 and 40 ft.

### Hydrogeology

CRREL is underlain by a single unconfined water table aquifer in the unconsolidated sediments and the bedrock (Arthur D. Little 1994). Depth to the water table ranges from 80 to 140 ft. Over most of the site, the aquifer occurs within the SM unit; along the western edge beneath the lower terrace, it also saturates the ML and the esker deposits. In the bedrock, ground water appears to move along discrete fractures. In the unconsolidated sediments, groundwater flows westward toward the esker, where water is withdrawn from production wells for the refrigeration system.

### Test well surroundings

The three wells evaluated in this study are screened within the brown fine silty sand (SM) unit. Depths to the bottoms of the 10-ft screens vary from 115 to 138 ft. As part of their remedial investigation, Arthur D. Little (1994) prepared a cross section that includes wells MW 09 and 11. Their location is shown in Figure B-1. Figure B-2 presents their interpreted cross section with MW 10 projected to an interpolated location along the path.

## Dover Air Force Base

### Geology

Dover AFB is located 3.5 miles southeast of the city of Dover in east central Delaware, about 2 miles from the Atlantic Ocean and bounded to the southwest by the St. Jones River. This area is within the Coastal Plain Physiographic Province, which is generally level with little topographic relief (Hunt 1967; Figure A-3). Surface elevation ranges from 10 to 35 ft above mean sea level (msl).

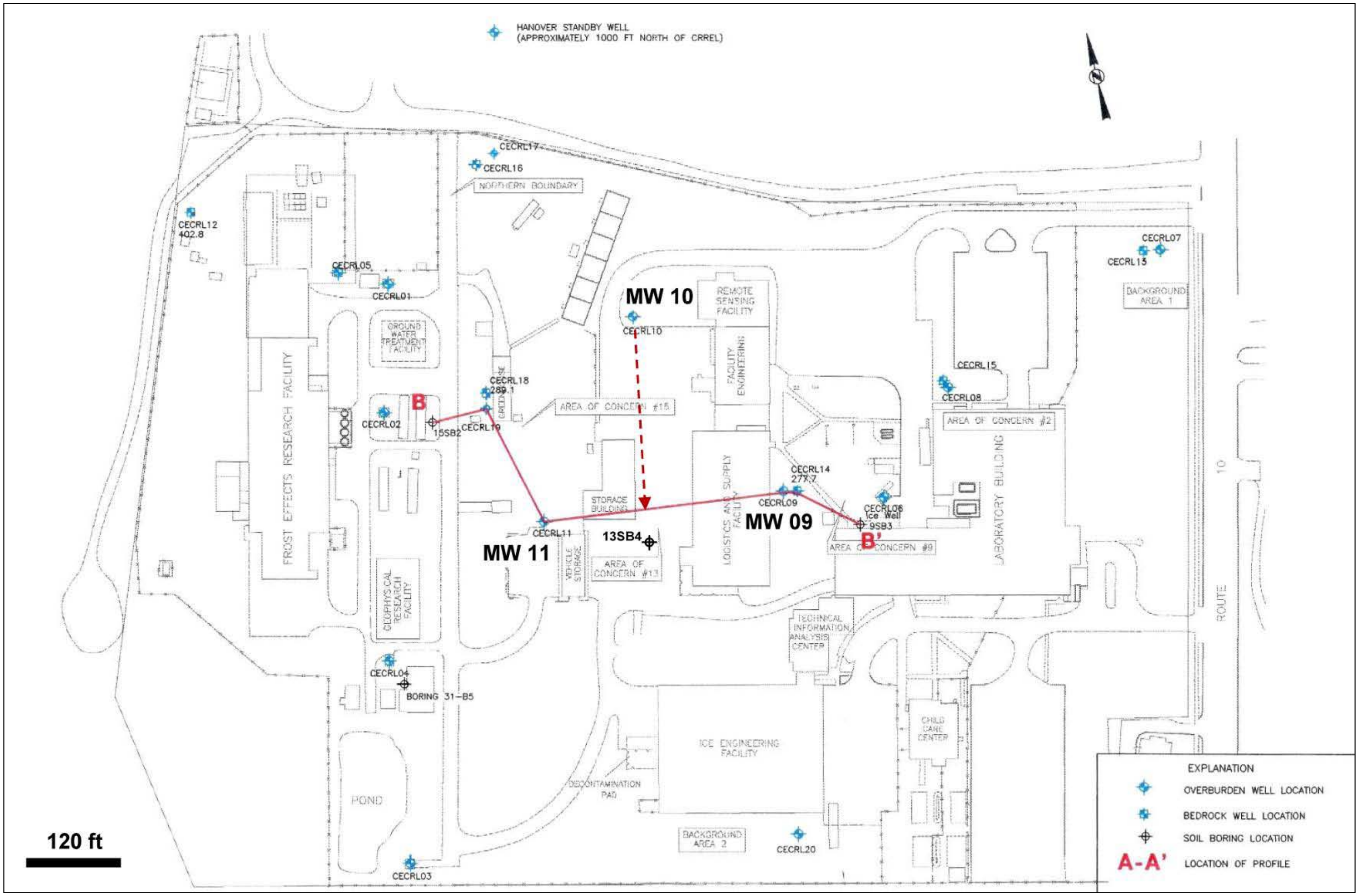


Figure B-1. Position of subsurface geological material cross section at CRREL site constructed by Arthur D. Little (1994) that includes wells MW 09 and MW 11 tested in this study. The figure shows how the third well (MW 10) was projected to a location between the other two wells in Figure B-2.

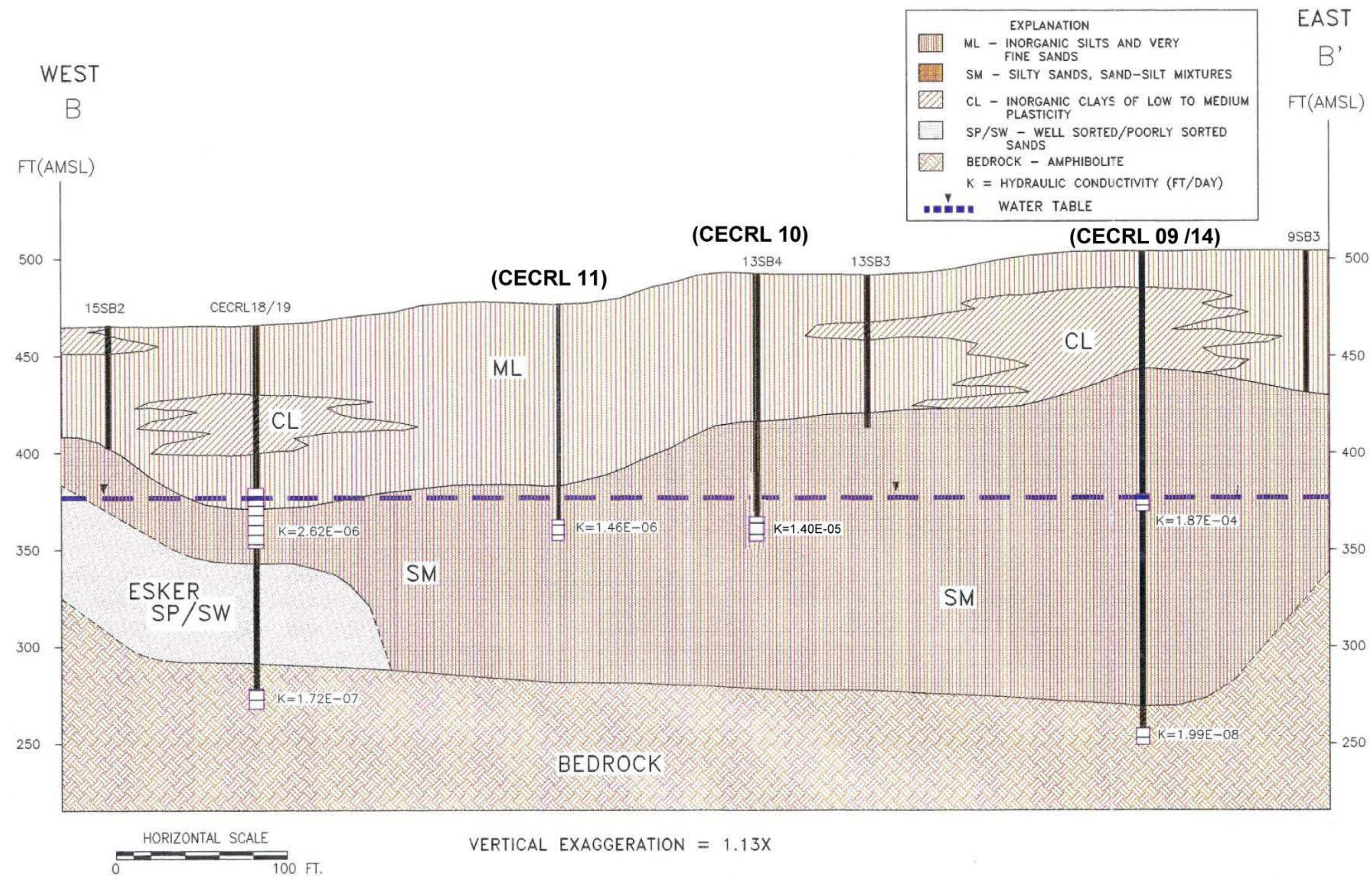


Figure B-2. CRREL subsurface geological material cross section constructed by Arthur D. Little (1994) that includes wells MW 09 and MW 11 (CECRL 09 and 11) tested in this study. The third well (MW 10, CECRL 10) is projected to a location between the other two wells. Its lithology is similar to Soil Boring 13SB4 that was included in the original construction.

The site is underlain by a wedge of unconsolidated sedimentary deposits that thicken to the southeast (Dames & Moore 1994, 1997). The surface deposit, referred to as the Columbia Formation, consists of Pleistocene glacial outwash deposits ranging in thickness between 30 and 70 ft to the base. These sandy deposits tend to coarsen with depth and contain clay, silt, and gravel lenses typical of meandering streams in an outwash plain. The formation lithology is described as fine-to-medium sand, with varying amounts of silt and clay lenses near the surface. The deeper portion consists of fine-to-coarse sand with less fine material. Underlying the Columbia Formation is the Miocene Calvert Formation, which includes five units of alternating clay and sand. An erosional event occurred between deposition of the Calvert and Columbia formations which formed an unconformable contact surface created by overlapping scour channels. The uppermost unit of the Calvert is a dense layer of dark gray clay and silt with fine sand laminations and variable thickness that depends on the local depth of the scouring. Under most of the base, it is 15- to 20-ft thick, but in a section near the central runway crossing, the layer is very thin or eroded away completely. This clay later acts as an aquitard between the Columbia Aquifer above, and the Frederica Aquifer in the upper sand unit of the Calvert. The sand unit ranges from 6- to 31-ft thick and is composed of fine-to-medium silty sand that grades to a less silty fine-to-coarse sand. It is confined below by the middle (~80-ft-thick) silt and clay unit of the Calvert Formation.

### Hydrogeology

The water table aquifer under Dover AFB is the saturated portion of the Columbia Formation called the Columbia Aquifer. The water table in the western portion of the base ranges from 16 ft bgs to within a few feet of the surface near the St. Jones River. Groundwater flow is generally to the south.

### Test well surroundings

The well clusters selected for this study are completed in the surficial (Columbia) aquifer. Depths to the base of the ~10-ft screens vary from 18 to 53 ft. The wells being tested are within 600 ft of a schematic cross section prepared by Dames & Moore (1994; Figure B-3). The section shown in Figure B-4 shows the spatial variability of the stratigraphic character in the area of wells MW 235, 236, and 237.

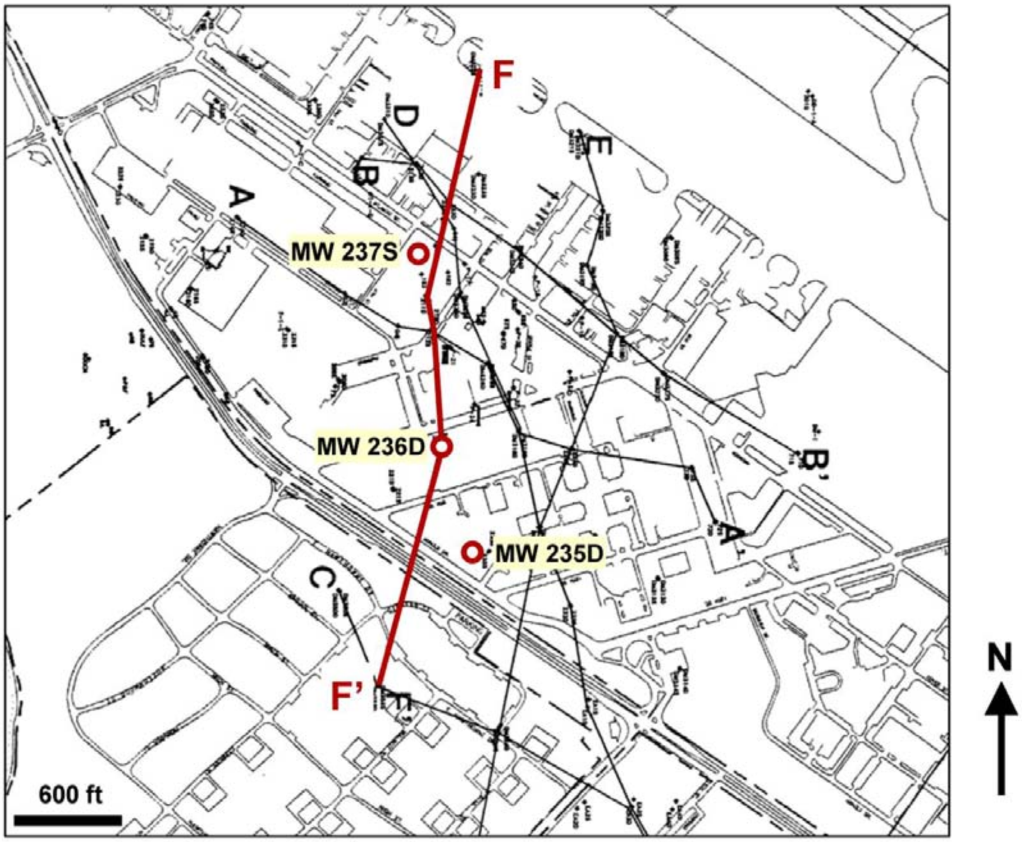


Figure B-3. Position of subsurface geological material cross sections at Dover AFB constructed by Dames & Moore (1994). Section F-F' (shown in red) includes MW 236D tested in this study. Locations of two other nearby tested wells are also shown.

## Hanscom Field and Hanscom Air Force Base

### Geology

Hanscom Field and Air Force Base are located approximately 14 miles northwest of Boston, MA in the Coastal Plain Physiographic Province (Figure A-2). The area is a low-lying basin surrounded by hills. The runway is on a flat plain with a general relief of less than 10 ft over approximately 3 miles distance. Bedrock-cored hills draped with glacial till and gravel are present to the south and east (80 ft relief) and the solitary lower Hartwells Hill (30 ft relief) is nearby to the north. The underlying bedrock is primarily a granitic sequence known as the Andover Granite, which includes a series of garnet-bearing, muscovite-biotite granites and pegmatite (Hepburn and Munn 1984).

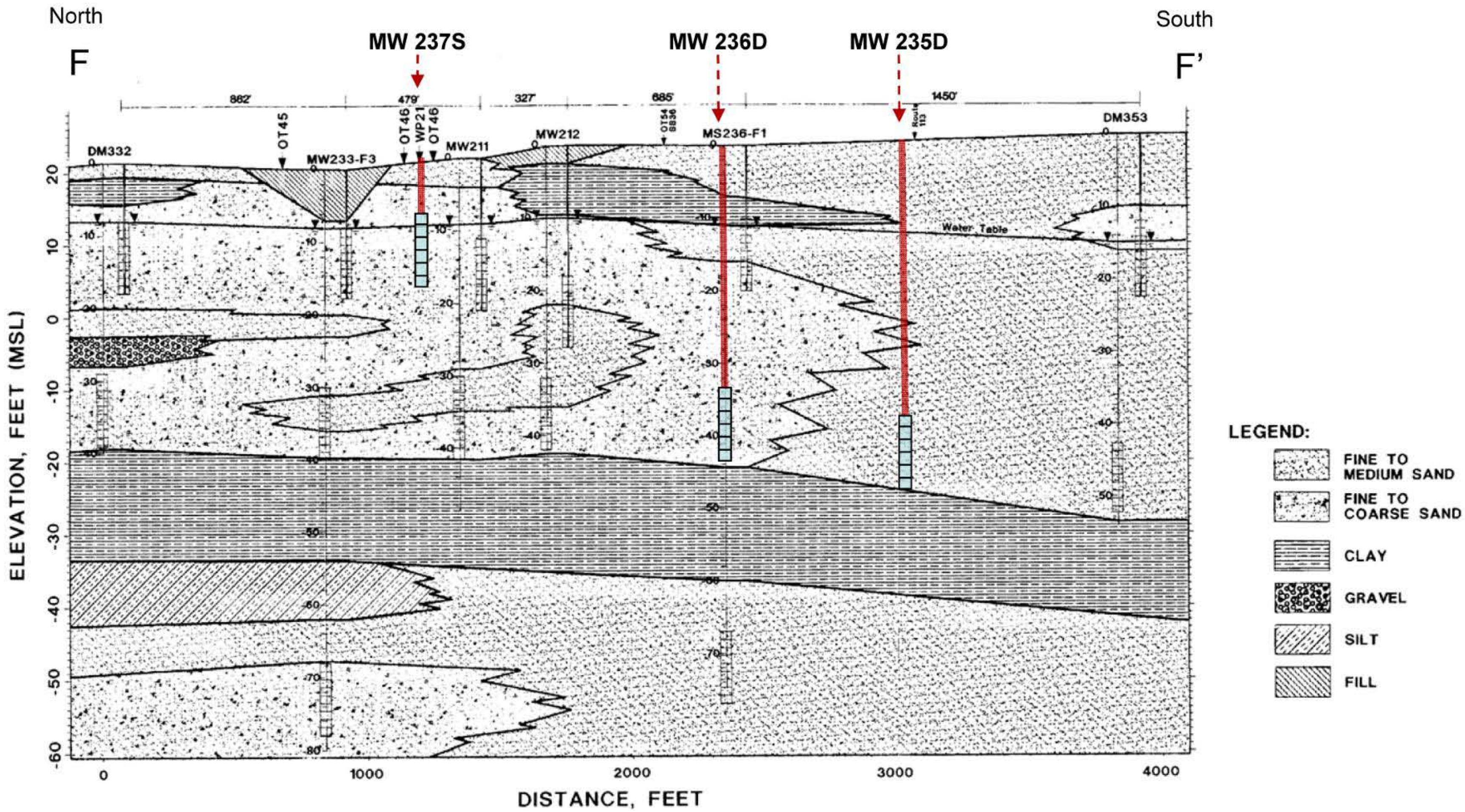


Figure B-4. Subsurface geological material cross section at Dover AFB constructed by Dames & Moore (1994) that includes well MW 236 tested in this study. The two other wells (MW 237S and 235D) are projected to locations at an equivalent distance along the section.

Erosional and depositional processes active during the Pleistocene glaciation modified the landscape in the region until the final retreat of glacial ice from the area approximately 13,000 years ago. As the ice retreated from the area, glacial meltwaters formed glacial Lake Concord between the ice front to the north and the hills south of Hanscom AFB. Glacial meltwaters transported and deposited sediments within the lake (CH2M Hill 2001).

In the vicinity of Hanscom AFB, glacial sediments consist mainly of the top-to-bottom sequence: glacial outwash materials (material deposited by glacial meltwaters), glacial lacustrine deposits formed in glacial Lake Concord, and glacial till deposits formed in contact with glacial ice (Figure B-5). The lacustrine deposits are discontinuous since Lake Concord did not submerge the topographically elevated areas. These elevated areas are generally composed of glacial till sediments and bedrock.

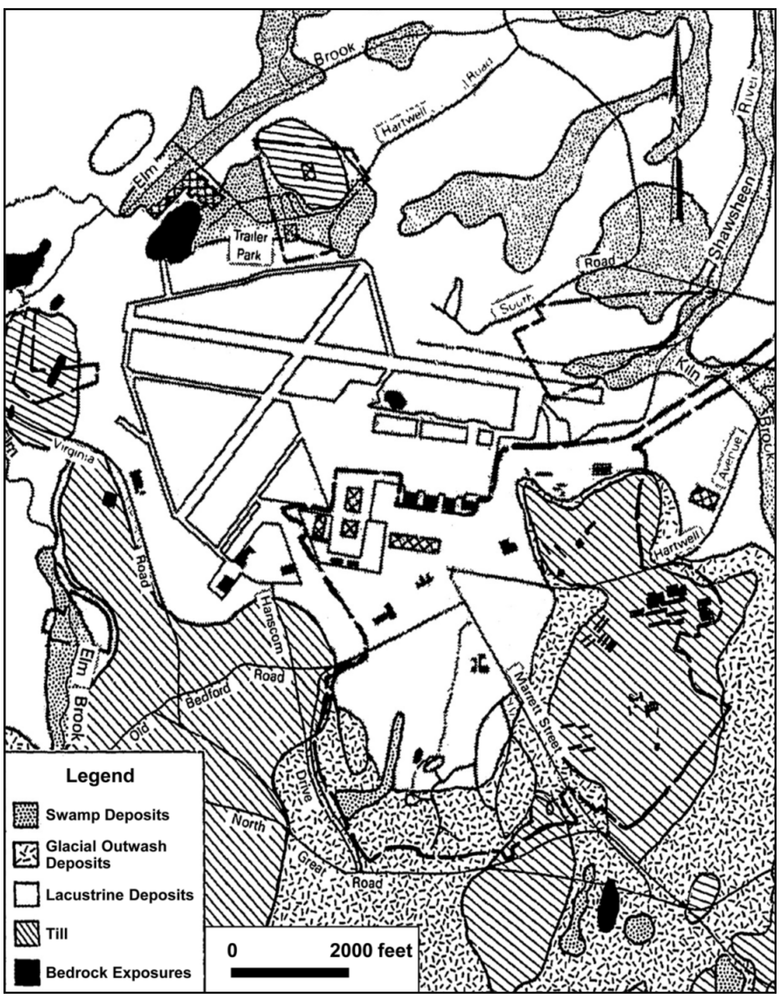

Figure B-5. Surficial geology of Hanscom Field (from JRB Associates 1984).

The uppermost outwash sediments are up to 33-ft thick and consist primarily of fine sand. Locally this unit is composed of medium to coarse sand with lesser amounts of gravel. The underlying glacial lacustrine (lake bed) sediments consist mainly of interbedded silt, clay, and fine sand grading with depth to clayey silts (JRB Associates 1984). Koteff (1964) indicated that the lacustrine sediments under Hanscom Field average 25 ft in thickness. These deposits overlie a discontinuous, thin lens of glacial till and, in some places, directly overlie bedrock. Glacial till immediately overlying bedrock around the Hanscom AFB consists of either a brown or gray coarse-to-fine sand with some gravel and silt (JRB Associates 1984).

### Hydrogeology

Principal surface drainage features at Hanscom Field/Hanscom AFB are the Shawsheen River, which originates in the east end of the air field and flows toward the northeast, and Elm Brook, which is located west of the airfield and ultimately flows northwest into the Shawsheen River.

The unconsolidated sediments from the top of bedrock to the ground surface can best be characterized by distinguishing between the low-lying areas of the glacial Lake Concord basin and the surrounding hills. In the ancient lake bed, the unconsolidated sediments are glacial and lacustrine deposits that form two transmissive zones separated by a semi-confining unit (Figures B-6 and B-7). The lower transmissive zone is in direct contact with the bedrock. It generally includes a sandy glacial till lying directly on the rock surface and a coarser sand-and-gravel outwash. The thickness of this unit varies from 0 to 60 ft, pinching out at the bases of the hills. Above this lower aquifer is a lacustrine silt and clay layer of relatively low hydraulic conductivity. This semi-confining unit is not continuous; it pinches out at the hills and has been eroded away under Elm Brook just north of Hartwells Hill. Its thickness varies from 0 to more than 50 ft. The upper transmissive zone is a lacustrine sand unit. In some areas this sand is well sorted, and in others it includes grain sizes ranging from very-fine sand and silt to fine gravel. The thickness of the lacustrine sand varies from 0 to 30 ft.

The hills are composed of a raised bedrock surface covered with glacial till. In some areas (such as Hartwells Hill), two types of till, sandy and clayey, have been identified. The clayey till generally lies directly on the bedrock

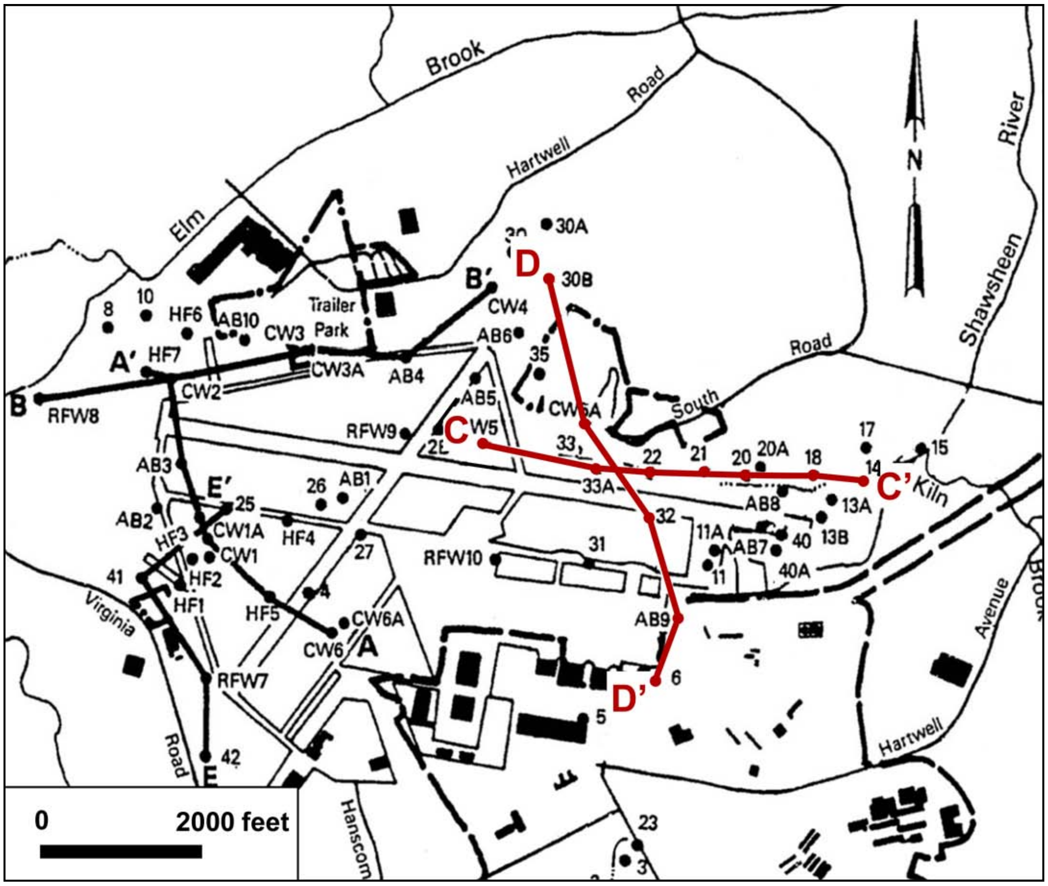


Figure B-6. **Position of subsurface geological material cross sections constructed by JRB Associates (1984).** Solid circles are locations of wells and borings. Cross Sections C-C' and D-D' (shown in red) are within the area of the Site 2 wells investigated in this study. Cross sections are shown in Figure B-7.

surface. It is quite dense and has a lower hydraulic conductivity than the sandy till. Its areal extent is also more limited. The sandy till consists of unsorted sand and silt with varying amounts of clay and gravel. It generally extends to the ground surface in the hilly areas.

### Test well surroundings

The well clusters studied in the Site 2 vicinity (see Figure A-2) are completed in the lower section of the upper transmissive lacustrine sand unit. Depths to the base of the 5- to 10-ft screens vary from 14 to 20 ft bgs. The wells are near two schematic cross sections prepared by JRB Associates (1984; Figures B-6 and B-7). On the east-west cross section (C-C'), they are near Well 33A; on the north-south (D-D') section, they are on either side of well CW5A.

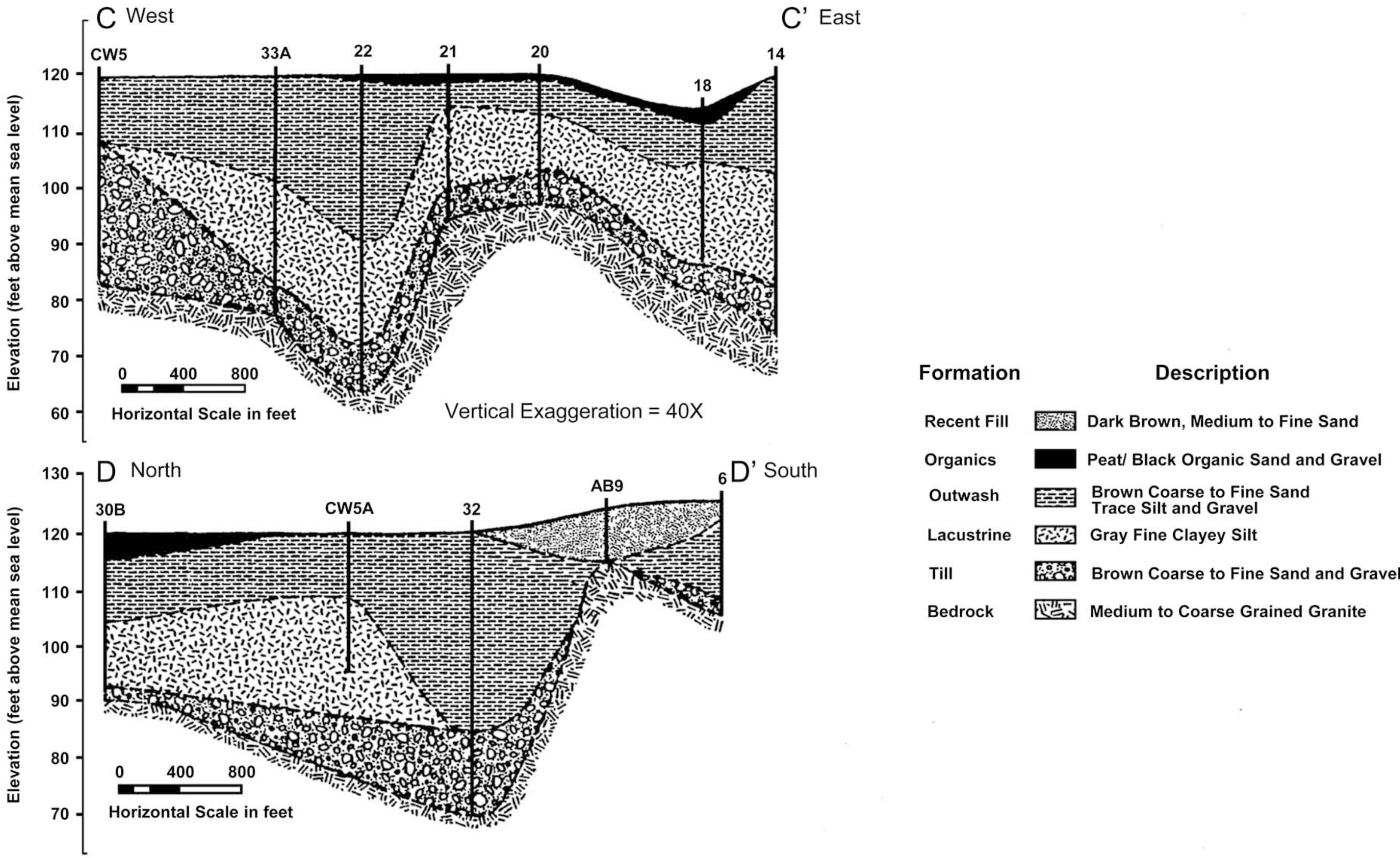


Figure B-7. Subsurface geological material cross sections constructed by JRB Associates (1984). The cross section locations are given in Figure B-6.

The two well clusters evaluated in the Site 21 area also have their screens within the lacustrine sand unit. They both have 10-ft screens with the bottoms at 18.5 and 22 ft. Unfortunately, the earlier prepared cross sections do not cross this part of the base.

## Tyndall Air Force Base

### Geology

Tyndall AFB is in the south-central Florida panhandle, just south of Panama City (see Figure A-4). This area is in the Gulf Coastal Lowlands portion of the Gulf Coastal Plain regional physiographic province (Hunt 1967). The lowlands are characterized by features such as beach ridges, barrier islands, lagoons, estuaries, and offshore bars created during Pleistocene Epoch eustatic sea level fluctuations. The base occupies the end of a northwest trending 16-mi-long peninsula (Figure A-4). Topography of the base is generally flat, with a maximum elevation of 34 ft above msl; in the region, maximum elevation reaches only 60 ft above msl.

The general geologic stratigraphy under Tyndall AFB has been well described by the Florida Bureau of Geology (1980) and the Navy Public Works Center (1997). Surface materials that include unconsolidated sands and a clayey sand unit overlie the Jackson Bluff Formation, the Intracoastal Formation, and the Bruce Creek Limestone (Figure B-8).

The study wells are screened in the most common surface material on base —unconsolidated loose to medium-dense well-sorted, fine- to medium-grained quartz sands. These sands are Pliocene to recent in age, moderately permeable and transmissive, extending to ~100-ft deep. The color varies from white to brown to various shades of gray (Sirrine 1992; Groundwater Services, Inc. 1995). Within the cleaner sand formation at various depths are lenses of tan to light-orange clayey sand, with traces of organic matter that can impede downward groundwater movement. This lithology probably results from the reworking of some higher hills during Pleistocene sea level fluctuations. Cone penetrometer studies by Rust Environment & Infrastructure (1998) found a layer of dense sand or silty sand at a depth of 12 to 15 ft bgs.

The unconsolidated sands are underlain by the Jackson Bluff Formation, a relatively thin (and in places, missing) blanket-type deposit consisting of relatively impermeable calcareous-sandy clay to clayey sand (Figure B-8).

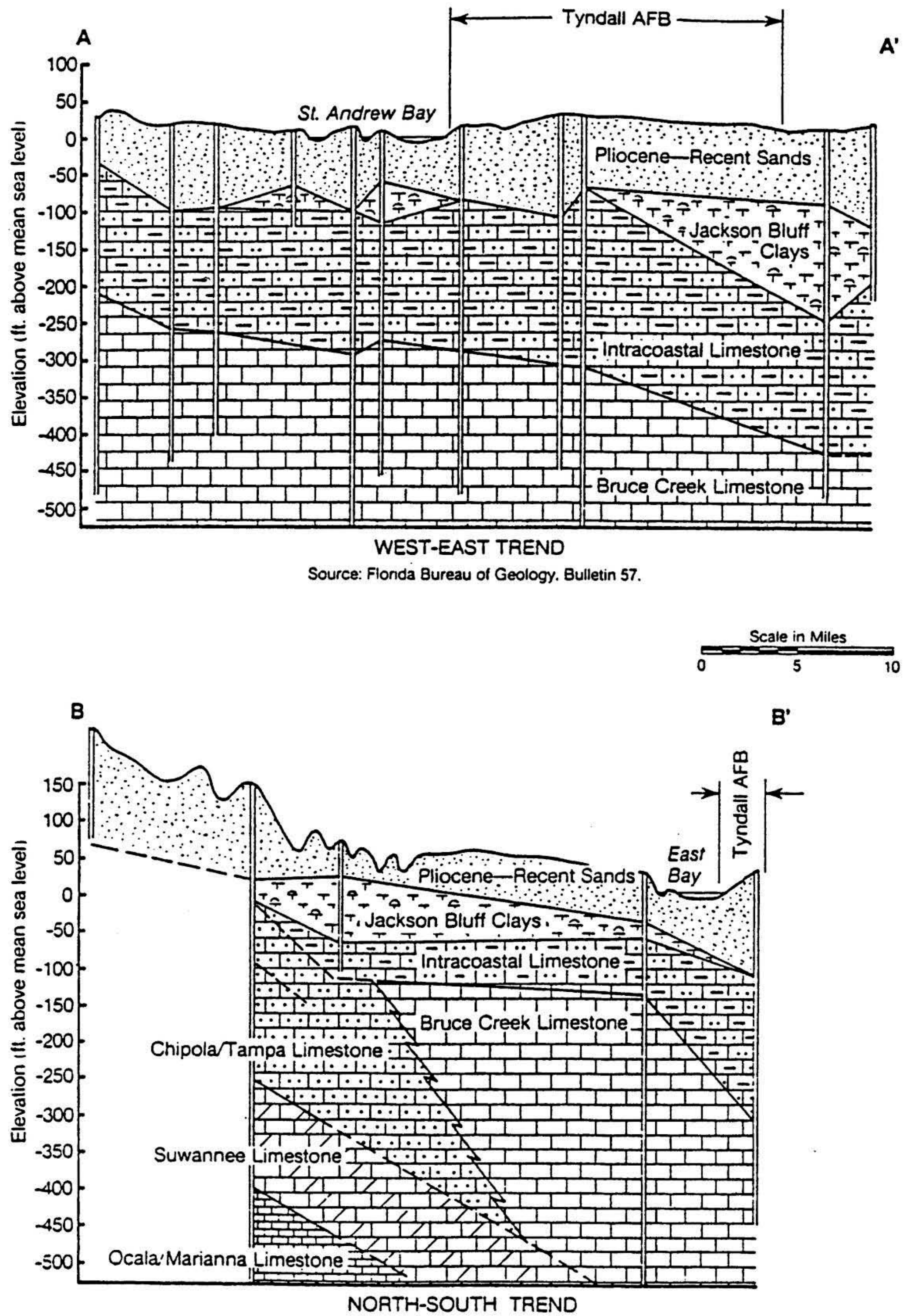


Figure B-8. General geologic stratigraphy beneath Tyndall Air Force Base. Data source is the Florida Bureau of Geology (1980). Figure prepared by CH2M Hill (1981).

Beneath the two above-described geologic units between 100 and approximately 330-ft deep is the Intracoastal Formation — a sandy, calcarenitic shell bed, with abundant foraminifera. The lithology includes fossil material, quartz sand, and calcium carbonate grains cemented by micrite and clay. The upper (Pliocene-age) portion is relatively impermeable; the lower (Miocene-age) portion is highly permeable. The deepest formation beneath the site from 330 ft to greater than 600 ft is the Bruce Creek Limestone — a white to light yellow-gray, moderately indurated, granular to calcarenitic limestone. Permeability is very high because of interconnected voids and solution cavities in the limestone (Navy Public Works Center 1997).

### Hydrogeology

Groundwater depths in the surficial Water Table Aquifer are very shallow, typically ranging from 2 to 7 ft bgs. The water table is relatively flat throughout Tyndall AFB; it typically fluctuates seasonally by 1 to 3 ft, but can vary up to 5 ft in response to seasonal rainfall and tidal cycles. A groundwater divide beneath Highway 98 separates areal flows to the northeast and southwest, but shallow groundwater flows toward nearby bayous, streams, and ditches (CH2M Hill 1981; Bergquist et al. 1997). Rust Environment & Infrastructure (1998) measured northeast trending groundwater flow in the wells near MW-02.

Two other aquifers are present at depth. The Shallow Artisan Aquifer lies within the Intracoastal Formation. The Floridan Aquifer System at depth is within the Bruce Creek Limestone and likely is interconnected with other deep limestone and dolomite beds beneath the state.

### Test well surroundings

The well clusters selected for this study are completed in the surficial water table aquifer. Depths to the base of the ~10-ft screens vary from 12 to 36 ft bgs. Well MW-02 is within 200 ft of schematic cross sections prepared by Rust Environment & Engineering (1998; Figure B-9). The sections show the consistency of the poorly graded sand unit and the frequency of clayey sand lenses within.

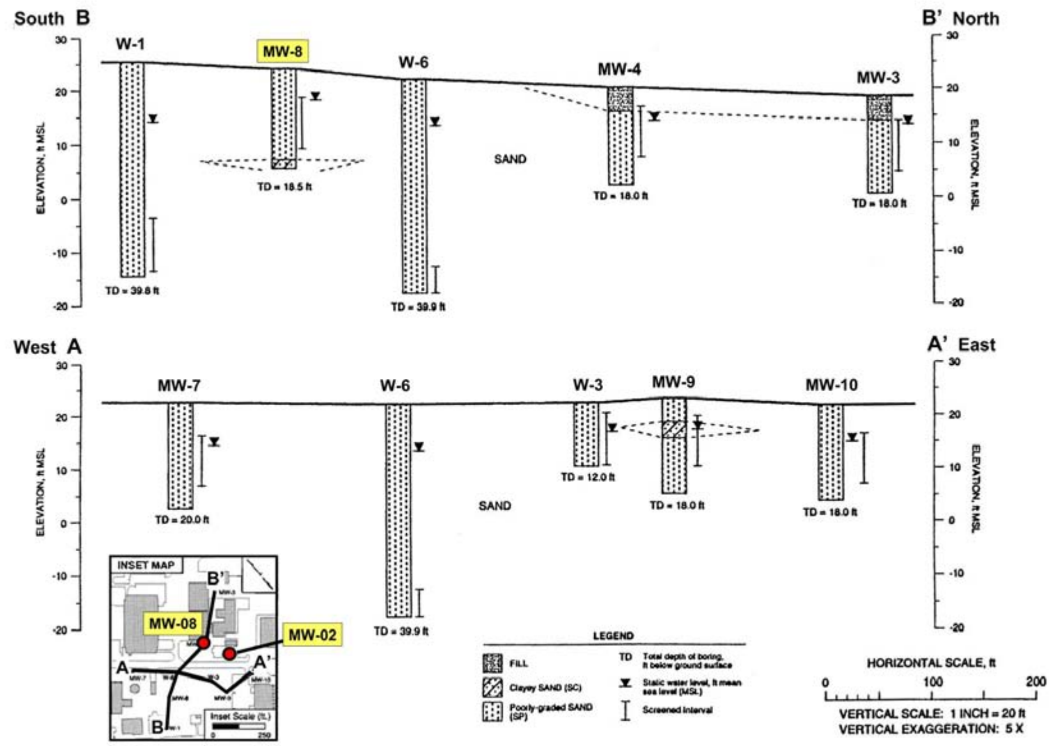


Figure B 9. Subsurface geological cross sections at Tyndall Air Force Base constructed by Groundwater Services, Inc. (1995) from data collected by Sirrine Environmental Consultants (1992) [W-1, -3, -6] and their studies [MW-3, -4, and MW-7 through -10]. Section B-B' includes MW-08 and is nearby MW-02 (about 200 ft away) that were tested in this study (see Inset).

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# Appendix C: Results

Table C-1. CRREL well construction details. All wells were constructed with PVC casing material and screens with a 0.010-in. slot size.

| | Well Information | | Screen Specifications | | |
|---|---|---|---|---|---|
| Cluster | Type[1] | Diameter[2] (in.) | Top (ft bgs) | Bottom (ft bgs) | Length (ft) |
| MW 09 | HSA | 4 | 126.5 | 136.5 | 10.0 |
| | DP | 1/2 | 129.0 | 138.0 | 9.0 |
| | DP | 3/4 | 127.0 | 137.0 | 10.0 |
| MW 10 | HSA | 4 | 117.0 | 127.0 | 10.0 |
| | DP | 1/2 | 117.5 | 126.5 | 9.0 |
| | DP | 3/4 | 117.0 | 127.0 | 10.0 |
| MW 11 | HSA | 4 | 106.5 | 116.5 | 10.0 |
| | DP | 1/2 | 105.5 | 114.5 | 9.0 |
| | DP | 3/4 | 106.5 | 116.5 | 10.0 |

[1] HSA = Hollow stem auger, DP = direct push
[2] Internal diameter
(Source: Major et al. 2009.)

Table C-2. Results from the slug tests performed at CRREL.

| Cluster | Well type | Rising-head tests | | Falling-head tests | |
|---|---|---|---|---|---|
| | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) |
| 9 | ¾-in. DP | 20.5 | 2.12 | 19.9 | 3.16 |
| | | 20.2 | 2.24 | 20.0 | 4.31 |
| | | 20.3 | 2.12 | 21.4 | 4.22 |
| | | 30.2 | 1.74 | 29.8 | 4.21 |
| | | 9.9 | 2.75 | 10.4 | 4.30 |
| | ½-in. DP | 19.7 | 3.63 | 20.2 | 2.53 |
| | | 20.5 | 3.48 | 19.8 | 2.59 |
| | | 20.0 | 3.52 | 20.1 | 2.44 |
| | | 30.0 | 2.95 | 31.0 | 2.48 |
| | | 9.8 | 3.81 | 11.0 | 2.61 |
| | HSA | 20.2 | 4.40 | 21.0 | 4.51 |
| | | 21.2 | 4.18 | 20.7 | 4.14 |
| | | 20.2 | 4.19 | | |
| | | 31.0 | 4.27 | | |
| | | | | 5.8 | 4.8 |
| | | 10.1 | 4.46 | 11.2 | 4.15 |
| 10 | ¾-in. DP | 25.0 | 8.39 | 20.2 | 8.11 |
| | | 20.5 | 8.12 | 20.0 | 8.25 |
| | | 20.3 | 7.10 | 19.3 | 8.25 |
| | | 20.5 | 8.57 | | |
| | | 30.3 | 7.95 | 30.7 | 7.12 |
| | | 10.2 | 8.84 | 9.9 | 7.88 |
| | ½-in. DP | 20.4 | 6.33 | 20.4 | 5.15 |
| | | 20.5 | 6.53 | 21.0 | 5.14 |
| | | | | 19.9 | 5.05 |
| | | 30.0 | 6.52 | 30.9 | 4.56 |
| | | 10.2 | 6.78 | 10.2 | 6.05 |
| | | 5.4 | 7.31 | 5.4 | 6.35 |
| | HSA | 20.3 | 2.44 | 23.2 | 2.73 |
| | | 20.3 | 2.76 | 21.4 | 2.62 |
| | | 28.8 | 2.40 | | |
| | | 10.8 | 2.60 | 9.1 | 2.70 |
| | | | | 5.2 | 2.92 |
| 11 | ¾-in. DP | 21.8 | 2.04 | 19.9 | 1.92 |
| | | 19.5 | 2.02 | 18.6 | 1.91 |
| | | 20.4 | 2.20 | 20.9 | 2.05 |
| | | 28.9 | 1.97 | 30.5 | 1.93 |
| | | 9.5 | 2.20 | 10.7 | 2.02 |
| | ½-in. DP | 20.2 | 0.48 | 19.5 | 0.44 |
| | | 20.2 | 0.47 | 20.9 | 0.42 |
| | | 19.0 | 0.46 | 21.2 | 0.43 |
| | | 28.0 | 0.47 | 30.2 | 0.45 |
| | | 10.4 | 0.50 | 11.8 | 0.43 |
| | | | | 4.7 | 0.41 |
| | HSA | 19.8 | 0.91 | 22.3 | 0.96 |
| | | 20.7 | 1.00 | | |
| | | 28.3 | 0.90 | | |
| | | 11.0 | 1.12 | 11.3 | 1.21 |
| | | | | 5.5 | 1.21 |

Table C-3. Reproducibility of replicate slug tests at CRREL site[1].

| Cluster | Well type | | Rising-head $H_o$ (in.) | Rising-head K (ft/d) | Falling-head $H_o$ (in.) | Falling-head K (ft/d) |
|---|---|---|---|---|---|---|
| 9 | ¾-in. DP | | 20.5 | 2.12 | 19.9 | |
| | | | 20.2 | 2.24 | 20.0 | 4.31 |
| | | | 20.3 | 2.12 | 21.4 | 4.22 |
| | | Mean | | 2.2 | | 3.9 |
| | | STD | | 0.069 | | 0.640 |
| | | RSD (%) | | 3.2 | | 16 |
| | ½-in. DP | | 19.7 | 3.63 | 20.2 | 2.53 |
| | | | 20.5 | 3.48 | 19.8 | 2.59 |
| | | | 20.0 | 3.52 | 20.1 | 2.44 |
| | | Mean | | 3.5 | | 2.5 |
| | | STD | | 0.078 | | 0.075 |
| | | RSD (%) | | 2.2 | | 3.0 |
| | HSA | | 20.2 | 4.40 | 21.0 | 4.51 |
| | | | 21.2 | 4.18 | 20.7 | 4.14 |
| | | | 20.2 | 4.19 | | |
| | | Mean | | 4.3 | | 4.3 |
| | | STD | | 0.125 | | 0.262 |
| | | RSD (%) | | 2.9 | | 6.0 |
| 10 | ¾-in. DP | | 20.5 | 8.12 | 20.0 | 8.25 |
| | | | 20.3 | 7.10 | 19.3 | 8.25 |
| | | | 20.5 | 8.57 | | |
| | | Mean | | 7.9 | | 8.3 |
| | | STD | | 0.752 | | 0.003 |
| | | RSD (%) | | 9.5 | | 0.03 |
| | ½-in. DP | | 20.4 | 6.33 | 20.4 | 5.15 |
| | | | 20.5 | 6.53 | 21.0 | 5.14 |
| | | | | | 19.9 | 5.05 |
| | | Mean | | 6.4 | | 5.1 |
| | | STD | | 0.144 | | 0.055 |
| | | RSD (%) | | 2.2 | | 1.1 |
| | HSA | | 20.3 | 2.44 | 23.2 | 2.73 |
| | | | 20.3 | 2.76 | 21.4 | 2.62 |
| | | | 28.8 | 2.40 | | |
| | | Mean | | 2.5 | | 2.7 |
| | | STD | | 0.197 | | 0.078 |
| | | RSD (%) | | 7.8 | | 2.9 |
| 11 | ¾-in. DP | | 21.8 | 2.04 | 19.9 | 1.92 |
| | | | 19.5 | 2.02 | 18.6 | 1.91 |
| | | | 20.4 | 2.20 | 20.9 | 2.05 |
| | | Mean | | 2.1 | | 2.0 |
| | | STD | | 0.099 | | 0.078 |
| | | RSD (%) | | 4.7 | | 4.0 |

[1] Pneumatic slug tests were used on all wells.

Table C-3 (Cont'd). Reproducibility of replicate slug tests at CRREL site.

| Cluster | Well type | | Rising-head | | Falling-head | |
|---|---|---|---|---|---|---|
| | | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) |
| | ½-in. DP | | 20.2 | 0.48 | 19.5 | 0.44 |
| | | | 20.2 | 0.47 | 20.9 | 0.42 |
| | | | 19.0 | 0.46 | 21.2 | 0.43 |
| | | Mean | | 0.5 | | 0.4 |
| | | STD | | 0.011 | | 0.006 |
| | | RSD (%) | | 2.4 | | 1.4 |
| | HS | | 19.8 | 0.91 | | |
| | | | 20.7 | 1.00 | | |
| | | | 28.3 | 0.90 | | |
| | | Mean | | 0.9 | | |
| | | STD | | 0.057 | | |
| | | RSD (%) | | 6.0 | | |

[1] Pneumatic slug tests were used on all wells.

Table C-4. Well construction details at Hanscom AFB.
All wells were constructed with PVC casing material

| Cluster | Well Information | | Screen Specifications | | |
|---|---|---|---|---|---|
| | Type[1] | Diameter[2] (in.) | Top (ft bgs) | Bottom (ft bgs) | Length (ft) |
| B107 | HSA | 2 | 4.0 | 14.0 | 10.0 |
| | DP | 2 | 4.09 | 13.93 | 9.84 |
| OW2-6 | HSA | 2 | 15.0 | 20.0 | 5.0 |
| | DP | 2 | 13.26 | 19.82 | 6.56 |
| RFW-11 | HSA | 2 | 7.2 | 17.2 | 10.0 |
| | DP | 2 | 7.22 | 17.06 | 9.84 |
| MWZ-6 | HSA | 2 | 8.5 | 18.5 | 10.0 |
| | DP | 2 | 8.94 | 18.78 | 9.84 |
| MWZ-11 | HSA | 2 | 12.0 | 22.0 | 10.0 |
| | DP | 2 | 10.09 | 19.93 | 9.84 |

[1] HSA = Hollow stem auger, DP = direct push
[2] Internal diameter
(Source: Major et al. 2009.)

Table C-5. Results from the slug tests at Hanscom AFB.

| Cluster | Rising-head tests | | | | | Falling-head tests | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Slug type | HSA well | | CPT well | | Slug type | HSA well | | CPT well | |
| | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) |
| MWZ 11 | PN | 18.5 | 1.014 | 9.8 | 0.544 | PA/PN | 21.7 | 0.844 | 9.8 | 0.478 |
| | | 19.9 | 0.824 | 10.8 | 0.561 | | 9.9 | 0.812 | 18.8 | 0.584 |
| | | 19.5 | 0.846 | 18.0 | 0.522 | | 5.4 | 0.927 | 28.9 | 0.683 |
| | | 23.8 | 0.807 | 5.0 | 0.593 | | | | | |
| | | 9.0 | 0.905 | | | | | | | |
| MWZ 6 | PN[1] | 16.9 | 0.445 | 10.0 | 0.684 | PA/PN | 21.0 | 1.52 | 20.2 | 0.486 |
| | | 20.2 | 0.398 | 9.7 | 0.664 | | 30.1 | 1.51 | 18.8 | 0.414 |
| | | 25.7 | 0.453 | 10.2 | 0.763 | | 11.6 | 2.43 | 20.2 | 0.442 |
| | | 21.7 | 0.542 | 13.5 | 0.62 | | | | 30.1 | 0.500 |
| | | 13.0 | 0.962 | 14.3 | 0.595 | | | | 10.4 | 0.524 |
| | | | | 4.9 | 0.645 | | | | | |
| B107 | MN[2] | 21.0 | 21.7 | 20.5 | 10.62 | MN[2] | 24 | 25.8 | 23.0 | 14.0 |
| | | 22.0 | 23.4 | 31.5 | 10.88 | | 25 | 29.2 | 24.5 | 14.4 |
| | | 11.0 | 23.3 | 23.2 | 10.33 | | 12 | 23.0 | 35.5 | 14. 9 |
| | | 10.0 | 22.6 | | | | 13 | 23.2 | 11.5 | 12.3 |
| | | 34.5 | 21.2 | | | | 36 | 25.5 | 12.2 | 13.9 |
| | | 36.0 | 24.3 | | | | 36 | 26.6 | | |
| OW2-6 | MN[2] | 18.0 | 2.59 | 12.0 | 3.98 | MN[2] | 25.0 | 3.71 | 24.0 | 4.19 |
| | | 37.0 | 2.58 | 26.5 | 3.59 | | 12.0 | 3.95 | 24.0 | 4.47 |
| | | 10.0 | 2.87 | 38.5 | 3.55 | | 35.3 | 4.28 | 36.0 | 4.55 |
| | | | | | | | 24.0 | 3.97 | 12.0 | 3.77 |
| RFW11 | MN[2] | 25.2 | 32.8 | 23.0 | 50.5 | MN[2] | 24.5 | 34.1 | 24.5 | 55.6 |
| | | 24.0 | 35.5 | 24.5 | 47.9 | | 24.8 | 31.8 | 25.0 | 50.7 |
| | | 12.5 | 28.7 | 12.5 | 49.0 | | 12.0 | 31.8 | 11.5 | 50.4 |
| | | 12.2 | 25.7 | 31.0 | 46.4 | | 11.5 | 33.5 | 12.5 | 55.7 |
| | | 28.0 | 32.5 | | | | 35.5 | 34.7 | 35.8 | 45.8 |
| | | | | | | | 12.0 | 29.5 | | |

PN = pneumatic test on casing; PA/PN = pneumatic test with packer; MN = 1-in. OD mandrel

[1]Upward concave normalized plots, especially for the falling-head tests. Possible bias?

[2] For the mandrel tests, $H_o$ is the distance the mandrel was lowered or raised to induce the head change. It was not the actual initial change in head that was induced in the well.

Table C-6. Results of replicate slug tests at Hanscom AFB.

| Cluster | Stat. | Rising-head tests | | | | Falling-head tests | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | HSA well | | CPT well | | HSA well | | CPT well | |
| | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) |
| MWZ 11 | | PN | | PA/PN | | | | | |
| | | 18.5 | 1.01 | 9.8 | 0.544 | | | | |
| | | 19.9 | 0.824 | 10.8 | 0.561 | | | | |
| | | 19.5 | 0.846 | | | | | | |
| | Mean | | 0.89 | | 0.55 | | | | |
| | STDEV | | 0.104 | | 0.012 | | | | |
| | RSD (%) | | 12 | | 2.2 | | | | |
| MWZ 6 | | PN | | PA/PN | | | | PA/PN | |
| | | 20.2 | 0.398 | 9.7 | 0.664 | | | 20.2 | 0.486 |
| | | 21.7 | 0.542 | 13.5 | 0.620 | | | 18.8 | 0.414 |
| | | 25.7 | 0.453 | 10.2 | 0.763 | | | 20.2 | 0.442 |
| | Mean | | 0.46 | | 0.68 | | | | 0.447 |
| | STDEV | | 0.073 | | 0.073 | | | | 0.036 |
| | RSD (%) | | 16 | | 10.7 | | | | 8.1 |
| B107 | | MN | | MN | | MN | | MN | |
| | | 21.0 | 21.67 | 20.5 | 10.62 | 24 | 25.81 | 23 | 13.99 |
| | | 22.0 | 23.43 | 23.2 | 10.33 | 25 | 29.20 | 24.5 | 14.35 |
| | Mean | | 22.6 | | 10.5 | | 27.5 | | 14.2 |
| | STDEV | | 1.24 | | 0.205 | | 2.40 | | 0.255 |
| | RSD (%) | | 5.5 | | 2.0 | | 8.7 | | 1.8 |
| | | 11.0 | 23.29 | | | 12 | 22.99 | 11.5 | 12.33 |
| | | 10.0 | 22.62 | | | 13 | 23.21 | 12.25 | 13.92 |
| | Mean | | 23.0 | | | | 23.1 | | 13.1 |
| | STDEV | | 0.474 | | | | 0.154 | | 1.12 |
| | RSD (%) | | 2.1 | | | | 0.7 | | 8.6 |
| | | 34.5 | 21.22 | | | 36 | 25.51 | | |
| | | 36.0 | 24.27 | | | 36 | 26.56 | | |
| | | 35.2 | | | | | | | |
| | Mean | | 22.7 | | | | 26.0 | | |
| | STDEV | | 2.2 | | | | 0.742 | | |
| | RSD (%) | | 9.5 | | | | 2.9 | | |
| OW2-6 | | | | | | MN | | MN | |
| | | | | | | 25.0 | 3.71 | 24.0 | 4.19 |
| | | | | | | 24.0 | 3.97 | 24.0 | 4.47 |
| | | | | | | 24.5 | | | |
| | Mean | | | | | | 3.8 | | 4.3 |
| | STDEV | | | | | | 0.184 | | 0.198 |
| | RSD (%) | | | | | | 4.8 | | 4.6 |

PN = pneumatic test on casing; PA/PN = pneumatic test with packer; MN = 1-in. OD mandrel.

Table C-6 (Cont'd). Results of replicate slug tests at Hanscom AFB.

| Cluster | Stat. | Rising-head tests | | | | Falling-head tests | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | HSA well | | CPT well | | HSA well | | CPT well | |
| | | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) | $H_o$ (in.) | K (ft/d) |
| RFW11 | | MN | | MN | | MN | | MN | |
| | | 25.2 | 32.85 | 23.0 | 50.5 | 24.5 | 34.10 | 24.5 | 55.6 |
| | | 24.0 | 35.51 | 24.5 | 47.9 | 24.8 | 31.80 | 25.0 | 50.7 |
| | Mean | | 34.2 | | 49.2 | | 33.0 | | 53.2 |
| | STDEV | | 1.88 | | 1.83 | | 1.63 | | 3.47 |
| | RSD (%) | | 5.5 | | 3.7 | | 4.9 | | 6.5 |
| | | 12.5 | 28.67 | | | 12.0 | 31.76 | 11.5 | 50.4 |
| | | 12.2 | 25.74 | | | 11.5 | 33.52 | 12.5 | 55.7 |
| | | | | | | 12.0 | 29.54 | | |
| | Mean | | 27.2 | | | | 31.6 | | 53.0 |
| | STDEV | | 2.07 | | | | 1.99 | | 3.77 |
| | RSD (%) | | 7.6 | | | | 6.3 | | 7.1 |

PN = pneumatic test on casing; PA = pneumatic test with packer; MN = 1-in. mandrel.

**Table C-7. Well construction details at Dover AFB.** All wells were constructed with PVC casing material.

| Well ID | Well Information | | Screen Specifications | | |
|---|---|---|---|---|---|
| | Type[1] | Diameter[2] (in.) | Top (ft bgs) | Bottom (ft bgs) | Length (ft) |
| DM-53S | HSA | 2 | 13.0 | 23.0 | 10.0 |
| NTS-53S | DP | 2 | 13.1 | 23.0 | 9.8 |
| DM-235D | HSA | 2 | 43.0 | 53.0 | 10.0 |
| NTS-235D | DP | 2 | 40.6 | 50.4 | 9.9 |
| NTS-235D (new) | DP | 2 | 43.2 | 53.8 | 10.6 |
| NTS-235DD | HSA (dup) | 2 | 43.3 | 53.3 | 10.0 |
| NTS-235DNP 3/4 | DP | 3/4 | 42.7 | 52.7 | 10.0 |
| NTS-235DP 3/4 | DP | 3/4 | 43.2 | 53.2 | 10.0 |
| MW-236D | HSA | 2 | 34.7 | 45.0 | 10.3 |
| NTS-236D | DP | 2 | 35.1 | 44.9 | 9.8 |
| NTS-236DD | HSA (dup) | 2 | 35.0 | 45.0 | 10.0 |
| NTS-236DNP 3/4 | DP | 3/4 | 35.0 | 45.0 | 10.0 |
| NTS-236DP 3/4 | DP | 3/4 | 35.0 | 45.0 | 10.0 |
| MW-237S | HSA | 2 | 8.4 | 18.5 | 10.1 |
| NTS-237S | DP | 2 | 8.6 | 18.4 | 9.8 |

1 HSA = Hollow stem auger, DP = direct push
2 Internal diameter
(Source: Major et al. 2009.)

Table C-8. Results from slug tests conducted at Dover AFB.

| Cluster | Well type | Test type | 2-in. CPT Slug Type | 2-in. CPT $H_o$ (in.) | 2-in. CPT K (ft/d) | 2-in. HSA Slug Type | 2-in. HSA $H_o$ (in.) | 2-in. HSA K (ft/d) | ¾-in. DP Slug Type | ¾-in. DP $H_o$ (in.) | ¾-in. DP K (ft/d) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 235 | Older well | FH | PN | 9.1 | 10.7 | PN | 9.7 | 30.6 | PN | 11.0 | 10.4 |
| | | | | 9.9 | 11.3 | | 10.2 | 30.5 | | 5.0 | 15.3 |
| | | | | 5.0 | 12.9 | | 5.0 | 30.1 | | 11.0 | 15.3 |
| | | | | 19.8 | 11.3 | | 20.1 | 27.5 | | 32.7 | 10.1 |
| | | RH | PN | 19.5 | 9.98 | PN | 20.5 | 30.3 | PN | 21.2 | 7.10 |
| | | | | 21.0 | 9.61 | | 20.7 | 29.6 | | 20.3 | 8.34 |
| | | | | 21.2 | 9.57 | | 21.0 | 29.0 | | 20.3 | 8.34 |
| | | | | 9.5 | 10.9 | | 10.4 | 30.7 | | 10.2 | 7.30 |
| | | | | 28.3 | 9.36 | | 29.5 | 27.4 | | 31.2 | 9.27 |
| | Duplicate | FH | PA/PN | 19.5 | 12.8 | PN | 19.5 | 12.8 | PN | 20.3 | 3.17 |
| | | | | 10.0 | 16.1 | | 10.0 | 16.1 | | 19.2 | 3.49 |
| | | | | 10.2 | 16.8 | | 10.2 | 16.8 | | 19.2 | 3.59 |
| | | | | 5.3 | 18.5 | | 5.3 | 18.5 | | 10.0 | 4.67 |
| | | RH | PA/PN | 20.5 | 15.1 | PN | 20.5 | 15.1 | PN | 20.9 | 2.56 |
| | | | | 22.4 | 14.6 | | 22.4 | 14.6 | | 19.8 | 2.79 |
| | | | | 20.4 | 14.7 | | 20.4 | 14.7 | | 20.0 | 3.05 |
| | | | | 10.0 | 16.7 | | 10.0 | 16.7 | | 10.1 | 3.90 |
| | | | | 30.2 | 13.8 | | 30.2 | 13.8 | | 30.0 | 2.74 |
| 236 | Older well | FH | PN | 19.8 | 51.2 | PN | 19.0 | 3.61 | PN | 21.1 | 1.57 |
| | | | | 20.3 | 50.5 | | 19.1 | 3.55 | | 20.2 | 1.46 |
| | | | | 20.4 | 54.0 | | 19.4 | 3.65 | | 21.0 | 1.37 |
| | | | | 9.8 | 56.6 | | 10.0 | 3.26 | | 9.90 | 1.18 |
| | | | | 30.0 | 53.0 | | 29.0 | 4.30 | | 30.3 | 1.40 |
| | | RH | PN | 22.8 | 55.0 | PN | 18.9 | 4.58 | PN | 19.0 | 1.87 |
| | | | | 24.2 | 55.4 | | 19.0 | 4.61 | | 19.6 | 2.01 |
| | | | | 20.7 | 55.4 | | 19.5 | 5.12 | | 19.7 | 2.07 |
| | | | | 9.8 | 55.9 | | 9.0 | 4.54 | | 10.0 | 1.88 |
| | | | | 29.8 | 55.4 | | 28.8 | 5.70 | | 29.0 | 2.14 |
| | Duplicate | | | | | PN | 18.6 | 1.70 | PN | 19.5 | 1.19 |
| | | | | | | | 18.0 | 1.73 | | 20.1 | 1.34 |
| | | | | | | | 30.1 | 1.82 | | 20.1 | 1.51 |
| | | | | | | | 10.0 | 1.65 | | 9.90 | 1.77 |
| | | | | | | PN | 16.8 | 2.38 | PN | 18.5 | 2.94 |
| | | | | | | | 9.0 | 2.21 | | 18.1 | 3.31 |
| | | | | | | | 4.1 | 2.20 | | 20.4 | 3.40 |
| | | | | | | | | | | 10.0 | 3.11 |
| | | | | | | | | | | 30.0 | 3.72 |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer.

Table C-8 (Cont'd). Results from slug tests conducted at Dover AFB.

| Cluster | Well type | Test type | 2-in. CPT Slug Type | 2-in. CPT $H_o$ (in.) | 2-in. CPT K (ft/d) | 2-in. HSA Slug Type | 2-in. HSA $H_o$ (in.) | 2-in. HSA K (ft/d) | ¾-in. DP Slug Type | ¾-in. DP $H_o$ (in.) | ¾-in. DP K (ft/d) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 237S | Older well | FH | PA/PN | 10.0 | 2.61 | PA/PN | 11.5 | 0.41 | | | |
| | | | | 10.0 | 2.20 | | 11.1 | 0.46 | | | |
| | | | | 10.0 | 2.55 | | 10.2 | 0.47 | | | |
| | | | | 5.0 | 2.87 | | 5.1 | 0.42 | | | |
| | | | | 19.9 | 1.98 | | | | | | |
| | | RH | PA/PN | 10.0 | 2.12 | PA/PN | 8.0 | 0.52 | | | |
| | | | | 10.0 | 2.01 | | 11.0 | 0.47 | | | |
| | | | | 10.0 | 1.88 | | 11.9 | 0.44 | | | |
| | | | | 5.0 | 2.80 | | 6.0 | 0.48 | | | |
| | | | | 19.9 | 2.32 | | | | | | |
| 53S | Older well | FH | PA/PN | 10.0 | 9.05 | PA/PN | 9.9 | 1.52 | | | |
| | | | | 5.0 | 9.46 | | 10.0 | 1.24 | | | |
| | | | | 9.8 | 9.60 | | 9.8 | 1.43 | | | |
| | | | | 9.8 | 9.60 | | 4.9 | 1.45 | | | |
| | | | | 19.9 | 7.67 | | 19.9 | 1.35 | | | |
| | | R | PA/PN | 10.8 | 8.42 | PA/PN | 10.1 | 1.13 | | | |
| | | | | 10.2 | 8.77 | | 10.0 | 1.15 | | | |
| | | | | 10.0 | 9.03 | | 10.0 | 1.38 | | | |
| | | | | 5.0 | 10.5 | | 5.0 | 1.28 | | | |
| | | | | 15.5 | 8.61 | | 20.0 | 1.22 | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer.

Table C-9. Results of replicate slug tests in older wells at Dover AFB.

| | | 2-in. CPT | | | 2-in. HSA | | | ¾-in. DP | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Test type | Slug type Stat | $H_o$ (in.) | K (ft/d) | Slug type Stat | $H_o$ (in.) | K (ft/d) | Slug type Stat | $H_o$ (in.) | K (ft/d) |
| 235 | RH | PN | 19.5 | 9.98 | PN | 20.5 | 30.3 | PN | 21.2 | 7.1 |
| | | | 21.0 | 9.61 | | 20.7 | 29.6 | | 20.3 | 8.34 |
| | | | 21.2 | 9.57 | | 21.0 | 29.0 | | 20.3 | 8.34 |
| | | Mean | | 9.7 | Mean | | 29.6 | Mean | | 7.9 |
| | | Std. dev. | | 0.226 | Std. dev. | | 0.651 | Std. dev. | | 0.716 |
| | | RSD (%) | | 2.3 | RSD (%) | | 2.2 | RSD (%) | | 9.0 |
| | FH | PN | 9.1 | 10.70 | PN | 9.7 | 30.6 | PN | 11.0 | 10.40 |
| | | | 9.9 | 11.30 | | 10.2 | 30.5 | | 11.0 | 15.30 |
| | | Mean | | 11.0 | Mean | | 30.6 | Mean | | 12.8 |
| | | Std. dev. | | 0.420 | Std. dev. | | 0.070 | Std. dev. | | 3.46 |
| | | RSD (%) | | 3.9 | RSD (%) | | 0.2 | RSD (%) | | 27.0 |
| 236 | RH | PN | 22.8 | 55.04 | PN | 18.9 | 4.58 | PN | 19.0 | 1.87 |
| | | | 24.2 | 55.44 | | 19.0 | 4.61 | | 19.6 | 2.01 |
| | | | 20.7 | 55.39 | | 19.5 | 5.12 | | 19.7 | 2.07 |
| | | Mean | | 55.3 | Mean | | 4.8 | Mean | | 2.0 |
| | | Std. dev. | | 0.218 | Std. dev. | | 0.304 | Std. dev. | | 0.103 |
| | | RSD (%) | | 0.4 | RSD (%) | | 6.4 | RSD (%) | | 5.2 |
| | FH | PN | 19.8 | 51.19 | PN | 19.0 | 3.61 | PN | 21.1 | 1.57 |
| | | | 20.3 | 50.51 | | 19.1 | 3.55 | | 20.2 | 1.46 |
| | | | 20.4 | 54.01 | | 19.4 | 3.65 | | 21.0 | 1.37 |
| | | Mean | | 51.9 | Mean | | 3.6 | Mean | | 1.5 |
| | | Std. dev. | | 1.86 | Std. dev. | | 0.050 | Std. dev. | | 0.100 |
| | | RSD (%) | | 3.6 | RSD (%) | | 1.4 | RSD (%) | | 6.8 |
| 237S | RH | PA/PN | 10.0 | 2.12 | PA/PN | 11.0 | 0.47 | | | |
| | | | 10.0 | 2.01 | | 11.9 | 0.44 | | | |
| | | | 10.0 | 1.88 | | | | | | |
| | | Mean | | 2.0 | Mean | | 0.46 | | | |
| | | Std. dev. | | 0.120 | Std. dev. | | 0.020 | | | |
| | | RSD (%) | | 6.0 | RSD (%) | | 4.7 | | | |
| | FH | PA/PN | 10.0 | 2.61 | PA/PN | 11.5 | 0.41 | | | |
| | | | 10.0 | 2.20 | | 11.1 | 0.46 | | | |
| | | | 10.0 | 2.55 | | 10.2 | 0.47 | | | |
| | | Mean | | 2.5 | Mean | | 0.4 | | | |
| | | Std. dev. | | 0.221 | Std. dev. | | 0.032 | | | |
| | | RSD (%) | | 9.0 | RSD (%) | | 7.2 | | | |
| 53S | RH | PA/PN | 10.8 | 8.42 | PA/PN | 10.1 | 1.13 | | | |
| | | | 10.2 | 8.77 | | 10.0 | 1.15 | | | |
| | | | 10.0 | 9.03 | | 10.0 | 1.38 | | | |
| | | Mean | | 8.7 | Mean | | 1.2 | | | |
| | | Std. dev. | | 0.306 | Std. dev. | | 0.139 | | | |
| | | RSD (%) | | 3.5 | RSD (%) | | 11.4 | | | |
| | FH | PA/PN | 10.0 | 9.05 | PA/PN | 9.9 | 1.52 | | | |
| | | | 9.8 | 9.60 | | 10.0 | 1.24 | | | |
| | | | 9.8 | 9.60 | | 9.8 | 1.43 | | | |
| | | Mean | | 9.4 | Mean | | 1.4 | | | |
| | | Std. dev. | | 0.318 | Std. dev. | | 0.143 | | | |
| | | RSD (%) | | 3.4 | RSD (%) | | 10.2 | | | |

RH = Rising-head test; FH = Falling-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer.

Table C-10. Results of replicate slug tests in the newer duplicate wells at Dover AFB.

| Cluster | Test type | 2-in. CPT duplicate well | | | 2-in. HSA duplicate well | | | ¾-in. DP duplicate well | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Slug Type Stat | $H_o$ (in.) | K (ft/d) | Slug Type Stat | $H_o$ (in.) | K (ft/d) | Slug Type Stat | $H_o$ (in.) | K (ft/d) |
| 235 | RH | PA/PN | 20.5 | 15.1 | PN | 20.5 | 15.1 | PN | 20.9 | 2.56 |
| | | | 22.4 | 14.6 | | 22.4 | 14.6 | | 19.8 | 2.79 |
| | | | 20.4 | 14.7 | | 20.4 | 14.7 | | 20.0 | 3.05 |
| | | Mean | | 14.8 | Mean | | 14.8 | Mean | | 2.8 |
| | | Std. dev. | | 0.265 | Std. dev. | | 0.265 | Std. dev. | | 0.245 |
| | | RSD (%) | | 1.8 | RSD (%) | | 1.8 | RSD (%) | | 8.8 |
| | FH | PA/PN | 10.0 | 16.1 | PN | 10.0 | 16.1 | PN | 20.3 | 3.17 |
| | | | 10.2 | 16.8 | | 10.2 | 16.8 | | 19.2 | 3.49 |
| | | | | | | | | | 19.2 | 3.59 |
| | | Mean | | 16.5 | Mean | | 16.5 | Mean | | 3.4 |
| | | Std. dev. | | 0.490 | Std. dev. | | 0.490 | Std. dev. | | 0.219 |
| | | RSD (%) | | 3.0 | RSD (%) | | 3.0 | RSD (%) | | 6.4 |
| | | | | | PN | 18.6 | 1.70 | | | |
| | | | | | | 18.0 | 1.73 | | | |
| | | | | | Mean | | 1.72 | | | |
| | | | | | Std. dev. | | 0.020 | | | |
| | | | | | RSD (%) | | 1.2 | | | |
| 236 | RH | | | | | | | PN | 18.5 | 2.94 |
| | | | | | | | | | 18.1 | 3.31 |
| | | | | | | | | | 20.4 | 3.40 |
| | | | | | | | | Mean | | 3.2 |
| | | | | | | | | Std. dev. | | 0.244 |
| | | | | | | | | RSD (%) | | 7.6 |
| | FH | | | | | | | PN | 19.5 | 1.19 |
| | | | | | | | | | 20.1 | 1.34 |
| | | | | | | | | | 20.1 | 1.51 |
| | | | | | | | | Mean | | 1.3 |
| | | | | | | | | Std. dev. | | 0.160 |
| | | | | | | | | RSD (%) | | 11.9 |

RH = Rising-head test; FH = Falling-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer.

Table C-11. Well construction details for Tyndall AFB.

| Well ID | Type | Type Key [1] | Screen Top (ft bgs) | Screen Bottom (ft bgs) | Screen Length (ft) |
|---|---|---|---|---|---|
| MW-1-C | 2” HSA | 1 | 3.0 | 13.0 | 10.0 |
| MW-1-P05 | 0.5” DP | 4 | 4.0 | 13.0 | 9.0 |
| MW-1-P10 | 1” DP | 3 | 3.0 | 13.0 | 10.0 |
| MW-1-P15 | 1.5” DP | 2 | 2.6 | 12.5 | 9.9 |
| MW-2-C | 2” HSA | 1 | 26.0 | 35.4 | 9.4 |
| MW-2-P05 | 0.5” DP | 4 | 27.0 | 36.0 | 9.0 |
| MW-2-P10 | 1” DP | 3 | 26.0 | 36.0 | 10.0 |
| MW-2-P15 | 1.5” DP | 2 | 25.7 | 35.6 | 9.9 |
| MW-5-C | 2” HSA | 1 | 1.5 | 11.5 | 10.0 |
| MW-5-P05 | 0.5” DP | 4 | 2.5 | 11.5 | 9.0 |
| MW-5-P10 | 1” DP | 3 | 1.5 | 11.5 | 10.0 |
| MW-5-P15 | 1.5” DP | 2 | 1.6 | 11.5 | 9.9 |
| MW-8-C | 2” HSA | 1 | 1.5 | 11.5 | 10.0 |
| MW-8-P05 | 0.5” DP | 4 | 2.5 | 11.5 | 9.0 |
| MW-8-P10 | 1” DP | 3 | 1.5 | 11.5 | 10.0 |
| MW-8-P15 | 1.5” DP | 2 | 1.6 | 11.5 | 9.9 |
| MWD-9-C | 2” HSA | 1 | 3.0 | 28.0 | 25.0 |
| MWD-9-P05 | 0.5” DP | 4 | 4.4 | 28.4 | 24.0 |
| MWD-9-P10 | 1” DP | 3 | 3.4 | 28.4 | 25.0 |
| MWD-9-P15 | 1.5” DP | 2 | 1.8 | 28.0 | 26.2 |
| MWD-11-C | 2” HSA | 1 | 3.0 | 28.0 | 25.0 |
| MWD-11-P05 | 0.5” DP | 4 | 4.4 | 28.4 | 24.0 |
| MWD-11-P10 | 1” DP | 3 | 3.5 | 28.5 | 25.0 |
| MWD-11-P15 | 1.5” DP | 2 | 1.8 | 28.0 | 26.2 |
| T-6-5C | 4” HSA | 1 | 4.0 | 19.0 | 15.0 |
| T-6-5C-New | 2” HSA New | 1 | | | |
| T-6-P05 | 0.5” DP | 4 | 4.0 | 19.0 | 15.0 |
| T-6-P10 | 1” DP | 3 | 4.0 | 19.0 | 15.0 |
| T-6-P15 | 1.5” DP | 2 | 2.6 | 19.0 | 16.4 |
| T-6-P15-New | 1.5” DP New | 2 | | | |

[1] Well Construction Type Key:
1. 2-in. "HSA" Conventional Sand Pack
2. 1.5-in. DP (Quasi-Static Installation)
3. 1-in. DP (Hammer Installation), Pre-pack
4. 1/2-in. DP (Hammer Installation), Pre-pack

Table C-12. Raw data for Tyndall AFB.

| Cluster | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MW 01 | 1-MN | RH | 4.8 | 23.2 | 1-MN | RH | 4.0 | 10.8 | 1-MN | RH | 12.0 | 17.4 | | | | |
| | | | 6.8 | 25.8 | | | 7.3 | 12.6 | | | 22.0 | 19.6 | | | could not | |
| | | | 12.3 | 22.8 | | | 12.3 | 12.8 | | | | | | | model data | |
| | | | 5.8 | 12.5 | | | 4.0 | 12.6 | | | | | | | | |
| | | FH | 5.3 | 37.5 | | FH | 3.5 | 9.18 | | FH | 13.0 | 17.6 | | | | |
| | | | 6.0 | 26.8 | | | 7.0 | 12.5 | | | 25.5 | 18.2 | | | | |
| | | | 12.0 | 15.7 | | | 12.8 | 12.1 | | | | | | | | |
| | | | 4.3 | 27.1 | | | 3.0 | 14.1 | | | | | | | | |
| MW 02 | PN | RH | 19.2 | 23.2 | PN | RH | 17.5 | 23.8 | PN | RH | 22.8 | 17.7 | PN | RH | 18.0 | 10.0 |
| | | | 19.2 | 23.6 | | | 9.5 | 26.2 | | | 19.8 | 14.9 | | | 19.0 | 9.62 |
| | | | 18.8 | 22.0 | | | 16.0 | 24.4 | | | 19.2 | 16.3 | | | 19.5 | 9.57 |
| | | | 9.0 | 22.8 | | | 14.0 | 23.8 | | | 9.5 | 15.8 | | | 12.2 | 9.88 |
| | | | 29.5 | 22.3 | | | | | | | 30.2 | 15.8 | | | 28.0 | 8.89 |
| | | FH | 19.2 | 24.1 | | FH | 18.0 | 30.0 | | FH | 19.8 | 17.2 | | FH | 22.6 | 10.9 |
| | | | 9.8 | 22.1 | | | 9.8 | 30.6 | | | 10.3 | 17.4 | | | 9.8 | 13.8 |
| | | | 4.8 | 25.2 | | | 4.7 | 35.9 | | | 5.0 | 19.6 | | | 4.3 | 13.8 |
| | 1-MN | RH | 12.8 | 61.1 | | | | | | | | | | | | |
| | | | 18.0 | 53.3 | | | | | | | | | | | | |
| | | | 37.2 | 54.9 | | | | | | | | | | | | |
| | | | 16.8 | 48.9 | | | | | | | | | | | | |
| | | FH | 12.0 | 49.8 | | | | | | | | | | | | |
| | | | 24.0 | 46.3 | | | | | | | | | | | | |
| | | | 36.0 | 48.1 | | | | | | | | | | | | |
| | | | 36.0 | 46.3 | | | | | | | | | | | | |
| | | | 37.2 | 48.1 | | | | | | | | | | | | |
| | | | 16.8 | 46.8 | | | | | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-12 (Cont'd). Raw data for Tyndall AFB.

| Cluster | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| T6-5 | PA/PN | RH | 20.0 | 1.57 | PA/PN | RH | 20.0 | 1.75 | ½ - MN | RH | nr | 6.05 | ½ - MN | RH | | |
| | | | 19.5 | 1.57 | | | 20.0 | 1.75 | | | nr | 6.05 | | | Unable to model | |
| | | | 19.5 | 1.57 | | | 20.0 | 1.75 | | | nr | 5.62 | | | spikey responses | |
| | | | 9.8 | 1.67 | | | 10.0 | 2.13 | | | nr | 2.02 | | | with available models | |
| | | | 30.0 | 1.16 | | | 30.0 | 1.86 | | | | | | | | |
| | | FH | 24.2 | 1.42 | | FH | 20.0 | 1.31 | | FH | nr | 3.45 | | FH | | |
| | | | 20.5 | 1.42 | | | 20.0 | 1.34 | | | nr | 1.69 | | | Unable to model | |
| | | | 20.1 | 1.47 | | | 20.0 | 1.41 | | | | | | | spikey responses | |
| | | | 10.1 | 1.73 | | | 20.0 | 1.44 | | | | | | | with available models | |
| | | | 29.9 | 1.16 | | | 10.0 | 1.75 | | | | | | | | |
| | | | 5.4 | 1.54 | | | 30.0 | 1.42 | | | | | | | | |
| | | | | | | New 1.5-in. CPT | | | | | | | | | | |
| | | | | | PA/PN | RH | 19.9 | 1.82 | | | | | | | | |
| | | | | | | | 19.9 | 1.78 | | | | | | | | |
| | | | | | | | 20.9 | 1.76 | | | | | | | | |
| | | | | | | | 10.2 | 2.26 | | | | | | | | |
| | | | | | | | 30.2 | 1.76 | | | | | | | | |
| | | | | | | FH | 20.1 | 1.73 | | | | | | | | |
| | | | | | | | 20.1 | 1.80 | | | | | | | | |
| | | | | | | | 20.0 | 1.62 | | | | | | | | |
| | | | | | | | 10.4 | 2.13 | | | | | | | | |
| | | | | | | | 29.8 | 1.71 | | | | | | | | |
| | | | | | | | 5.2 | 2.71 | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-12 (Cont'd). Raw data for Tyndall AFB.

| Cluster | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MW 05 | PA/PN | RH | 19.4 | 1.99 | PA/PN | RH | 20.0 | 0.746 | 12-MN | RH | 16.6 | 14.2 | BT | RH | 10.8 | 0.73 |
| | | | 20.0 | 2.66 | | | 19.9 | 0.726 | | | 17.8 | 19.2 | | | 11.5 | 0.585 |
| | | | 19.8 | 2.73 | | | 20.0 | 0.617 | | | | | | | 15.3 | 0.699 |
| | | | 10.0 | 2.44 | | | 10.0 | 0.716 | | | | | | | 16.9 | 0.687 |
| | | | 29.5 | 2.64 | | | 30.0 | 0.702 | | | | | | | 18.0 | 0.55 |
| | | | | | | | 5.0 | 0.806 | | | | | | | | |
| | | FH | 20.1 | 2.24 | | FH | 20.0 | 0.903 | | FH | 14.0 | 21.5 | | | | |
| | | | 19.8 | 2.27 | | | 20.0 | 0.796 | | | 13.0 | 24.9 | | | | |
| | | | 19.8 | 2.10 | | | 20.0 | 0.776 | | | 13.5 | 20.1 | | | | |
| | | | 9.8 | 2.50 | | | 10.0 | 0.873 | | | 25.6 | 18.9 | | | | |
| | | | 29.8 | 2.33 | | | 30.0 | 0.776 | | | | | | | | |
| MW 08 | PA/PN | RH | 20.0 | 2.52 | ½-MN | RH | 12.3 | 5.39 | 12-MN | RH | 11.5 | 9.62 | BT | RH | 9.8 | 1.39 |
| | | | 20.0 | 2.57 | | | 12.0 | 6.27 | | | 12.3 | 6.31 | | | 21.5 | 1.93 |
| | | | 20.0 | 2.12 | | | 12.1 | 5.97 | | | 25.5 | 10.9 | | | 21.0 | 1.93 |
| | | | 10.2 | 1.99 | | | 12.0 | 7.00 | | | 24.0 | 10.55 | | | | |
| | | | 27.8 | 1.95 | | | | | | | | | | | | |
| | | FH | 20.0 | 2.18 | | FH | 12.0 | 7.99 | | FH | 12.0 | 11.90 | | FH | 6.8 | 1.97 |
| | | | 20.0 | 2.20 | | | 24.0 | 6.19 | | | 24.0 | 11.60 | | | | |
| | | | 21.0 | 2.19 | | | 24.0 | 6.34 | | | 24.5 | 11.20 | | | | |
| | | | 10.0 | 2.39 | | | 23.8 | 7.21 | | | | | | | | |
| | | | 30.0 | 2.22 | | | | | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-12 (Cont'd). Raw data for Tyndall AFB.

| | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MWD 09 | PA/PN | RH | 20.4 | 1.56 | PA/PN? | RH | 20.8 | 3.46 | MN | RH | 16.1 | 0.869 | NG | RH | | |
| | | | 20.5 | 1.67 | | | 20.0 | 3.46 | | | | | | | could not model | |
| | | | 20.6 | 1.67 | | | 20.8 | 3.46 | | | anomalous | | | | anomalous | |
| | | | 10.0 | 1.94 | | | 10.0 | 4.29 | | | responses | | | | responses | |
| | | | 30.0 | 1.67 | | | 31.8 | 2.48 | | | | | | | | |
| | | FH | 20.2 | 1.34 | | FH | 19.9 | 3.88 | | FH | 24.0 | 0.79 | | FH | | |
| | | | 19.9 | 1.34 | | | 20.6 | 3.76 | | | 12.5 | 0.79 | | | anomalous | |
| | | | 9.8 | 1.57 | | | 10.5 | 4.23 | | | | | | | responses | |
| | | | 29.8 | 1.21 | | | 30.2 | 3.34 | | | | | | | | |
| | | | | | | | 10.2 | 4.09 | | | | | | | | |
| | | | | | | RH | 20.2 | 1.78 | | RH | 11.5 | 9.62 | BT | RH | 9.8 | 1.39 |
| | | | | | | | 20.1 | 1.78 | | | 12.3 | 6.31 | | | 21.5 | 1.93 |
| | | | | | | | 20.0 | 1.78 | | | 25.5 | 10.9 | | | 21.0 | 1.93 |
| | | | | | | | 9.9 | 2.35 | | | 24.0 | 10.55 | | | | |
| | | | | | | | 4.8 | 3.38 | | | | | | | | |
| | | | | | | | 15.0 | 2.23 | | | | | | | | |
| | | | | | | FH | 19.9 | 4.15 | | FH | 12.0 | 11.90 | | FH | 6.8 | 1.97 |
| | | | | | | | 20.1 | 4.14 | | | 24.0 | 11.60 | | | | |
| | | | | | | | 19.9 | 3.98 | | | 24.5 | 11.20 | | | | |
| | | | | | | | 10.1 | 4.23 | | | | | | | | |
| | | | | | | | 5.0 | 4.60 | | | | | | | | |
| | | | | | | | 15.0 | 4.65 | | | | | | | | |
| | | | | | | | 30.0 | 4.65 | | | | | | | | |
| MWD 11 | PA/PN | RH | 20.0 | 1.25 | no test; well head collapsed | | | | NG | | | | NG | | | |
| | | | 18.0 | 1.39 | | well abandoned | | | | | could not | | | | could not | |
| | | | 19.9 | 1.34 | | | | | | | model data | | | | model data | |
| | | | 10.0 | 1.53 | | | | | | | | | | | | |
| | | | 29.8 | 1.13 | | | | | | | | | | | | |
| | | FH | 20.2 | 1.43 | | | | | | | | | | | | |
| | | | 19.5 | 1.53 | | | | | | | | | | | | |
| | | | 20.6 | 1.66 | | | | | | | | | | | | |
| | | | 10.0 | 1.99 | | | | | | | | | | | | |
| | | | 29.8 | 1.58 | | | | | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-13. Results of replicate slug tests at Tyndall AFB.

| | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MW 01 | 1-MN | RH | 4.8 | 23.2 | 1-MN | RH | 4.0 | 10.8 | | | | | | | | |
| | | | 6.8 | 25.8 | | | 4.0 | 12.6 | | | | | | | | |
| | | | 5.8 | 12.5 | | | | | | | | | | | | |
| | | | Mean | 20.5 | | | Mean | 11.7 | | | | | | | | |
| | | | Std Dev | 7.05 | | | Std Dev | 1.27 | | | | | | | | |
| | | | RSD (%) | 34 | | | RSD (%) | 11 | | | | | | | | |
| | | FH | 5.3 | 37.5 | | | 3.5 | 9.18 | | | | | | | | |
| | | | 6.0 | 26.8 | | | 3.0 | 14.10 | | | | | | | | |
| | | | 4.3 | 27.1 | | | | | | | | | | | | |
| | | | Mean | 30.5 | | | Mean | 11.64 | | | | | | | | |
| | | | Std Dev | 6.09 | | | Std Dev | 3.48 | | | | | | | | |
| | | | RSD (%) | 20 | | | RSD (%) | 30 | | | | | | | | |
| MW 02 | PN | RH | 19.2 | 23.2 | PN | RH | 17.5 | 23.8 | PN | RH | 22.8 | 17.7 | PN | RH | 18.0 | 10.0 |
| | | | 19.2 | 23.6 | | | 16.0 | 24.4 | | | 19.8 | 14.9 | | | 19.0 | 9.62 |
| | | | 18.8 | 22.0 | | | 14.0 | 23.8 | | | 19.2 | 16.3 | | | 19.5 | 9.57 |
| | | | Mean | 22.9 | | | Mean | 24.0 | | | Mean | 16.3 | | | Mean | 9.73 |
| | | | Std Dev | 0.833 | | | Std Dev | 0.346 | | | Std Dev | 1.40 | | | Std Dev | 0.235 |
| | | | RSD (%) | 3.6 | | | RSD (%) | 1.4 | | | RSD (%) | 8.6 | | | RSD (%) | 2.4 |
| | 1-MN | RH | 18.0 | 53.3 | | | | | | | | | | | | |
| | | | 16.8 | 48.9 | | | | | | | | | | | | |
| | | | Mean | 51.1 | | | | | | | | | | | | |
| | | | Std Dev | 3.11 | | | | | | | | | | | | |
| | | | RSD (%) | 6.1 | | | | | | | | | | | | |
| | | FH | 36.0 | 48.1 | | | | | | | | | | | | |
| | | | 36.0 | 46.3 | | | | | | | | | | | | |
| | | | 37.3 | 48.1 | | | | | | | | | | | | |
| | | | Mean | 47.5 | | | | | | | | | | | | |
| | | | Std Dev | 1.04 | | | | | | | | | | | | |
| | | | RSD (%) | 2.2 | | | | | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-13 (Cont'd). Results of replicate slug tests at Tyndall AFB.

| Cluster | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MW 05 | PA/PN | RH | 19.4 | 1.99 | PA/PN | RH | 20.0 | 0.746 | 12-MN | RH | 16.6 | 14.2 | BT | RH | 10.8 | 0.730 |
| | | | 20.0 | 2.66 | | | 19.9 | 0.726 | | | 17.8 | 19.2 | | | 11.5 | 0.585 |
| | | | 19.8 | 2.73 | | | 20.0 | 0.617 | | | | | | | 15.3 | 0.699 |
| | | | | | | | | | | | | | | | 16.9 | 0.687 |
| | | | Mean | 2.5 | | | Mean | 0.7 | | | Mean | 16.7 | | | Mean | 0.68 |
| | | | Std Dev | 0.409 | | | Std Dev | 0.069 | | | Std Dev | 3.54 | | | Std Dev | 0.063 |
| | | | RSD (%) | 17 | | | RSD (%) | 10 | | | RSD (%) | 21 | | | RSD (%) | 9.3 |
| | | FH | 20.1 | 2.24 | | FH | 20.0 | 0.903 | | FH | 14.0 | 21.5 | | | | |
| | | | 19.8 | 2.27 | | | 20.0 | 0.796 | | | 13.0 | 24.9 | | | | |
| | | | 19.8 | 2.10 | | | 20.0 | 0.776 | | | 13.5 | 20.1 | | | | |
| | | | Mean | 2.2 | | | Mean | 0.80 | | | Mean | 22.2 | | | | |
| | | | Std Dev | 0.091 | | | Std Dev | 0.068 | | | Std Dev | 2.47 | | | | |
| | | | RSD (%) | 4.1 | | | RSD (%) | 8.3 | | | RSD (%) | 11 | | | | |
| MW 08 | PA/PN | RH | 20.0 | 2.52 | ½-MN | RH | 12.3 | 5.39 | 12-MN | RH | 11.5 | 9.62 | BT | RH | 21.5 | 1.93 |
| | | | 20.0 | 2.57 | | | 12.0 | 6.27 | | | 12.3 | 6.31 | | | 21.0 | 1.93 |
| | | | 20.0 | 2.12 | | | 12.1 | 5.97 | | | | | | | | |
| | | | | | | | 12.0 | 7.00 | | | | | | | | |
| | | | Mean | 2.4 | | | Mean | 6.16 | | | Mean | 7.96 | | | Mean | 1.93 |
| | | | Std Dev | 0.247 | | | Std Dev | 0.670 | | | Std Dev | 2.34 | | | Std Dev | 0 |
| | | | RSD (%) | 10 | | | RSD (%) | 11 | | | RSD (%) | 29 | | | RSD (%) | 0 |
| | | | | | | | | | | RH | 25.5 | 10.9 | | | | |
| | | | | | | | | | | | 24.0 | 10.6 | | | | |
| | | | | | | | | | | | Mean | 10.7 | | | | |
| | | | | | | | | | | | Std Dev | 0.247 | | | | |
| | | | | | | | | | | | RSD (%) | 2.3 | | | | |
| | | FH | 20.0 | 2.18 | | FH | 24.0 | 6.19 | | FH | 24.0 | 11.6 | | | | |
| | | | 20.0 | 2.20 | | | 24.0 | 6.34 | | | 24.5 | 11.2 | | | | |
| | | | 21.0 | 2.19 | | | 23.8 | 7.21 | | | | | | | | |
| | | | Mean | 2.19 | | | Mean | 6.58 | | | Mean | 11.4 | | | | |
| | | | Std Dev | 0.010 | | | Std Dev | 0.551 | | | Std Dev | 0.283 | | | | |
| | | | RSD (%) | 0.50 | | | RSD (%) | 8.4 | | | RSD (%) | 2.5 | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-13 (Cont'd). Results of replicate slug tests at Tyndall AFB.

| | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Slug Type | Test Type | $H_0$ (in.) | K (ft/d) | Slug Type | Test Type | $H_0$ (in.) | K (ft/d) | Slug Type | Test Type | $H_0$ (in.) | K (ft/d) | Slug Type | Test Type | $H_0$ (in.) | K (ft/d) |
| MWD 09 | PA/PN | RH | 20.4 | 1.56 | PA/PN | RH | 20.8 | 3.46 | | | | | | | | |
| | | | 20.5 | 1.67 | | | 20.0 | 3.46 | | | | | | | | |
| | | | 20.6 | 1.67 | | | 20.8 | 3.46 | | | | | | | | |
| | | | Mean | 1.63 | | | Mean | 3.46 | | | | | | | | |
| | | | Std Dev | 0.064 | | | Std Dev | 0 | | | | | | | | |
| | | | RSD (%) | 3.9 | | | RSD (%) | 0 | | | | | | | | |
| | | FH | 20.2 | 1.34 | | FH | 19.9 | 3.88 | | | | | | | | |
| | | | 19.9 | 1.34 | | | 20.6 | 3.76 | | | | | | | | |
| | | | Mean | 1.34 | | | Mean | 3.82 | | | | | | | | |
| | | | Std Dev | 0 | | | Std Dev | 0.085 | | | | | | | | |
| | | | RSD (%) | 0 | | | RSD (%) | 2.2 | | | | | | | | |
| | | | | | | FH | 10.5 | 4.23 | | | | | | | | |
| | | | | | | | 10.2 | 4.09 | | | | | | | | |
| | | | | | | | Mean | 4.16 | | | | | | | | |
| | | | | | | | Std Dev | 0.099 | | | | | | | | |
| | | | | | | | RSD (%) | 2.4 | | | | | | | | |
| | | | | | | RH | 20.2 | 1.78 | | | | | | | | |
| | | | | | | | 20.1 | 1.78 | | | | | | | | |
| | | | | | | | 20.0 | 1.78 | | | | | | | | |
| | | | | | | | Mean | 1.78 | | | | | | | | |
| | | | | | | | Std Dev | 0 | | | | | | | | |
| | | | | | | | RSD (%) | 0 | | | | | | | | |
| | | | | | | FH | 19.9 | 4.15 | | | | | | | | |
| | | | | | | | 20.1 | 4.14 | | | | | | | | |
| | | | | | | | 19.9 | 3.98 | | | | | | | | |
| | | | | | | | Mean | 4.09 | | | | | | | | |
| | | | | | | | Std Dev | 0.095 | | | | | | | | |
| | | | | | | | RSD (%) | 2.3 | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-13 (Cont'd). Results of replicate slug tests at Tyndall AFB.

| | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| MWD 11 | PA/PN | RH | 20.0 | 1.25 | | | | | | | | | | | | |
| | | | 18.0 | 1.39 | | | | | | | | | | | | |
| | | | 19.9 | 1.34 | | | | | | | | | | | | |
| | | | Mean | 1.33 | | | | | | | | | | | | |
| | | | Std Dev | 0.071 | | | | | | | | | | | | |
| | | | RSD (%) | 5.3 | | | | | | | | | | | | |
| | | FH | 20.2 | 1.43 | | | | | | | | | | | | |
| | | | 19.5 | 1.53 | | | | | | | | | | | | |
| | | | 20.6 | 1.66 | | | | | | | | | | | | |
| | | | Mean | 1.54 | | | | | | | | | | | | |
| | | | Std Dev | 0.115 | | | | | | | | | | | | |
| | | | RSD (%) | 7.5 | | | | | | | | | | | | |
| T6-5 | PA/PN | RH | 20.0 | 1.57 | PA/PN | RH | 20.0 | 1.75 | | | | | | | | |
| | | | 19.5 | 1.57 | | | 20.0 | 1.75 | | | | | | | | |
| | | | 19.5 | 1.57 | | | 20.0 | 1.75 | | | | | | | | |
| | | | Mean | 1.57 | | | Mean | 1.75 | | | | | | | | |
| | | | Std Dev | 0 | | | Std Dev | 0 | | | | | | | | |
| | | | RSD (%) | 0 | | | RSD (%) | 0 | | | | | | | | |
| | | FH | 24.2 | 1.42 | | FH | 20.0 | 1.31 | | | | | | | | |
| | | | 20.5 | 1.42 | | | 20.0 | 1.34 | | | | | | | | |
| | | | 20.1 | 1.47 | | | 20.0 | 1.41 | | | | | | | | |
| | | | | | | | 20.0 | 1.44 | | | | | | | | |
| | | | Mean | 1.44 | | | Mean | 1.38 | | | | | | | | |
| | | | Std Dev | 0.029 | | | Std Dev | 0.060 | | | | | | | | |
| | | | RSD (%) | 2.0 | | | RSD (%) | 4.4 | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

Table C-13 (Cont'd). Results of replicate slug tests at Tyndall AFB.

| Cluster | 2-in. HSA | | | | 1.5-in. CPT | | | | 1-in. DP | | | | 0.5-in. DP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) | Slug Type | Test Type | $H_o$ (in.) | K (ft/d) |
| T6-5 | | | | | | New 1.5-in. CPT | | | | | | | | | | |
| | | | | | PA/PN | RH | 19.9 | 1.82 | | | | | | | | |
| | | | | | | | 19.9 | 1.78 | | | | | | | | |
| | | | | | | | 20.9 | 1.76 | | | | | | | | |
| | | | | | | | Mean | 1.79 | | | | | | | | |
| | | | | | | | Std Dev | 0.031 | | | | | | | | |
| | | | | | | | RSD (%) | 1.7 | | | | | | | | |
| | | | | | | FH | 20.1 | 1.73 | | | | | | | | |
| | | | | | | | 20.1 | 1.80 | | | | | | | | |
| | | | | | | | 20.0 | 1.62 | | | | | | | | |
| | | | | | | | Mean | 1.72 | | | | | | | | |
| | | | | | | | Std Dev | 0.091 | | | | | | | | |
| | | | | | | | RSD (%) | 5.3 | | | | | | | | |

FH = Falling-head test; RH = Rising-head test; PN = Pneumatic test; PA/PN = Pneumatic test with packer;
1-MN = 1-in. ID mandrel; ½-MN = 0.5-in. ID mandrel; 12-MN = 12-mm OD mandrel; BT = Bare transducer; NG = Not given.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
8Mar2011

**2. REPORT TYPE**
Final Report

**3. DATES COVERED** *(From - To)*

**4. TITLE AND SUBTITLE**
Comparison of Hydraulic Conductivity in Direct-Push Monitoring Wells and Co-Located Conventional Monitoring Wells

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
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**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

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**8. PERFORMING ORGANIZATION REPORT NUMBER**
ERDC/CRREL TR-11-6

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Headquarters
U.S. Army Corps of Engineers
Washington, DC 20314-1000

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Determination of the hydraulic conductivity of a formation is needed for site assessment and remediation. This project examined whether direct-push (DP) monitoring wells can provide a measure of formation hydraulic conductivity similar to that provided by conventionally installed hollow-stem auger (HSA) wells using single-well test methods (i.e., slug tests). Four test sites with co-located DP and HSA wells were used. Soil types at the test sites were primarily fine- to medium-sized sands. DP-well installation methods included both hydraulically driven cone penetrometer (CPT) wells and hammered wells. The CPT wells typically relied on formation collapse around the well screen to form the filter pack. The remaining DP wells were constructed with pre-pack filters. The DP wells ranged in diameter from 1/2 in. to 2 in., and the lengths and depths of the screens were matched as closely as possible to those of the HSA wells. Whenever possible, pneumatic slug tests were performed. Where the wells were screened across the water table, however, a packer was used in conjunction with the pneumatic test in the larger wells and a mandrel test method was used in the smaller wells.

**15. SUBJECT TERMS**
K determinations
Hydraulic conductivity measurements
Hydraulic conductivity
Slug tests
Direct-push wells

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)* |
|---|---|---|---|---|---|
| U | U | U | U | 90 | |

**Standard Form 298 (Rev. 8-98)**
**Prescribed by ANSI Std. 239.18**